



# **ROBUST TRACKING SYSTEM IN FRONT OF RADIO- FREQUENCY INTERFERENCES. PART III: SIGNALS, MODULATIONS, AND RELIABILITY ANALYSIS**

**A Degree Thesis**

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**by**

**Adrià Gil Sorribes**

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of the requirements for the degree in  
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**Advisors:**

**Mr. Jorge Querol Borràs**

**Prof. Adriano José Camps Carmona**

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## **Abstract**

The aim of this project is to simulate and implement a Robust Tracking System (RTS), capable of tracking a transmitter when Global Position System (GPS) signals are not available, offering high resistance to Radio Frequency Interference signals (RFI). This is a project developed in the Theory of the Signal and Communication (TSC) Department in the Universitat Politècnica de Catalunya (UPC).

RTS combines the use of the hyperbolic navigation techniques; the Least Mean Squares (LMS) algorithm, to estimate the transmitter position; and the use of a spread-spectrum signal modulation, in order to achieve greater robustness against RFI signals. A study and comparison of the different spread-spectrum modulations is performed in order to find out the best one and an implementation with the available hardware is designed to examine the performance of this modulation in a real scenario.

The spread-spectrum modulation that has proven to be the best for the system is the Frequency Hopping Spread-Spectrum (FHSS) since it is the one that provides a greater Signal-to-Interference Ratio (SIR) after the demodulation has been performed. Future work will be oriented to the design of an application that would gather all the information and present it to the final user in a more visual way.

## **Resum**

L'objectiu d'aquest projecte és simular i implementar un sistema capaç de rastrejar un transmissor quan el sistema de posicionament global (GPS) no està disponible, un sistema que ofereixi una alta resistència als senyals ràdio interferents, anomenat Robust Tracking System (RTS). Es tracta d'un projecte desenvolupat al Departament de Teoria del Senyal i Comunicacions (TSC) a la Universitat Politècnica de Catalunya (UPC).

RTS combina l'ús de les tècniques de navegació hiperbòlica; el mètode de mínims quadrats, per estimar la posició del transmissor; i l'ús d'una modulació de senyal d'espectre eixamplat, per tal d'aconseguir una major robustesa enfront de senyals ràdio interferents. S'ha realitzat un estudi, així com una comparació de les diferents modulacions d'espectre eixamplat per determinar la millor i implementar-la usant el hardware disponible per examinar, d'aquesta manera, el comportament del sistema en un escenari real.

La modulació d'espectre eixamplat que ha demostrat ser la millor per al sistema és la "Frequency Hopping Spread-Spectrum" (FHSS), ja que és la que proporciona una major relació de senyal a interferent un cop s'ha fet la desmodulació del senyal rebut. Un treball per al futur podria ser el disseny d'una aplicació que reuneixi tota la informació del sistema i la presenti a l'usuari final d'una manera visual i interactiva.

## **Resumen**

El objetivo de este proyecto es simular e implementar un sistema capaz de rastrear un transmisor cuando el sistema de posicionamiento global (GPS) no está disponible, un sistema que ofrezca una alta resistencia a las señales interferentes de radio, llamado *Robust Tracking System* (RTS). Se trata de un proyecto desarrollado en el Departamento de Teoría de la Señal y Comunicaciones (TSC) en la Universidad Politécnica de Cataluña (UPC).

RTS combina el uso de las técnicas de navegación hiperbólica; el método de mínimos cuadrados, para estimar la posición del transmisor; y el uso de una modulación de señal de espectro ensanchado, con el fin de lograr una mayor robustez frente a señales radio interferentes. Se ha realizado un estudio, así como una comparación de las diferentes modulaciones de espectro ensanchado para determinar la mejor e implementarla usando el hardware disponible para examinar, de este modo, el comportamiento del sistema en un escenario real.

La modulación de espectro ensanchado que ha demostrado ser la mejor para el sistema es la "Frequency Hopping Spread-Spectrum" (FHSS), ya que es la que proporciona una mayor relación de señal a interferente una vez se ha hecho la demodulación de la señal recibida. Un trabajo para el futuro podría ser el diseño de una aplicación que reúna toda la información del sistema y la presente al usuario final de una manera visual e interactiva.

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Name	e-mail
Adrià Gil Sorribes	adriagil.94@gmail.com
Jorge Querol	jorge.querol@tsc.upc.edu
Adriano Camps	camps@tsc.upc.edu

Written by:		Reviewed and approved by:	
Date	06/06/2016	Date	27/06/2016
Name	Adria GIL SORRIBES	Name	Jorge QUEROL BORRÀS Adriano José CAMPS CARMONA
Position	Project Author	Position	Project Supervisors

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## 1. Introduction

The project has been carried out at the department of Signal Theory and Communications (TSC) of UPC-BarcelonaTech, and in particular, in the Remote Sensing Laboratory (RSLab) research group, which has experience in designing and implementation of Radio-Frequency Interference (RFI) detection and mitigation systems.

### 1.1. RTS: the Robust Tracking System

Nowadays, the electromagnetic spectrum is becoming more and more used due to the growing presence of wireless electronic devices emitting and receiving electromagnetic radiation. This fact fosters the appearance of the Radio Frequency Interference (RFI) phenomenon. RFI signals are perturbations that affect any nearby electrical circuit and can be problematic for any kind of receiver, especially for those systems that work with very low power signal. An example is the Global Navigation Satellite System (GNSS) and more particularly the Global Positioning System (GPS) known as the most widely used location system. As GPS is used in the vast majority of tracking and positioning applications, it has begun a research and development of new systems able to overcome the RFI drawback. To this end, new interference mitigation techniques have been proposed, and also, the use of signal modulations that increase robustness against interference are under study. The Robust Tracking System (RTS), using the Time Difference of Arrival (TDOA) localization technique and a ground-based infrastructure, intends to be a reliable solution for one of these applications such as moving objects tracking.

Recently, position determination technique using TDOA method has been broadly used in many applications such as in mobile phones tracking, for example. This is a popular hyperbolic navigation methodology as it uses time difference of signal arrival from target to fixed receivers. The strength of TDOA based localization method is that synchronization is unnecessary between receivers. Due to this characteristic, TDOA has been used extensively in real time locating systems. To solve TDOA equations, the Least mean squares (LMS) algorithm is used.

One example already working that uses the technology explained before is the eLoran positioning, navigation and timing service. eLoran is an independent, dissimilar, complement to Global Navigation Satellite Systems (GNSS) allowing GNSS users to retain the safety, security, and economic benefits of GNSS, even when their satellite services are disrupted.

The RTS must use the technology explained above combined with the use of the called spread spectrum modulations in order to gain robustness against the radiofrequency interferences and jamming. Hereby, RTS might be used in applications that require high reliability such as transport of dangerous goods or vehicle tracking, applications that cannot afford any failure caused by an RFI signal and thus, they cannot trust a common GPS system.

## 1.2. **Statement of purpose**

The project deals with the implementation of a Robust Tracking System (RTS), and in particular, with the front-end configuration and the reliability analysis. The RTS must be reliable in front of the growing problem of Radio-Frequency Interference (RFI), which degrades, or even disrupts, the performance of tracking systems based on the Global Navigation Satellite Systems (GNSS).

For this reason, the main purpose of the project is to study through MATLAB simulations which modulation would achieve the best performance in front of RFI signals. After the simulation has been done, the chosen modulation will be implemented using the available hardware and will be tested in order to confirm, or deny, the simulation results. Then, a reliability analysis will show how strong the modulation is in front of some specific RFI and which are the optimum parameters in order to have the best possible performance.

Once the tests have been finished, the intention was to attach the three parts of the system and perform a final experiment in a more real scenario in order to observe the performance of the whole Robust Tracking System (RTS) but, as it will be explained in 1.6 it has not been possible.

## 1.3. **Requirements and specifications**

### Project requirements:

- Implement a modulation strong enough to maximize the robustness of the system in front of Radio Frequency Interference.
- Based on other studies already done, a spread-spectrum modulation will be used since they have a fortress against interference that can help us meet the first requirement of this list
- The fact that the tracked mobile is only transmitting will represent that it cannot be jammed by RFI signals. On the other hand, the receiver stations can be affected by jamming, these stations are static and thus, the RFI signals effect can be controlled.
- Under no interference conditions, GPS positioning of the nodes will be used as an auxiliary subsystem.

### Project specifications:

- Minimum receiver sensitivity: -100 dBm. RTL-SDR R820T2 specifications.
- Bit rate is 115.2 kbps.
- Duty cycle is 1 second but without synchronism between nodes.
- The power gain at the transmitter will be set up to achieve a working range of the order of 100 km.
- UHF band (433 MHz) is used to reduce propagation losses as compared to S-band (2.4 GHz) for example.
- Rejection factor against RFI signals as higher as possible.

#### 1.4. Methods and procedures

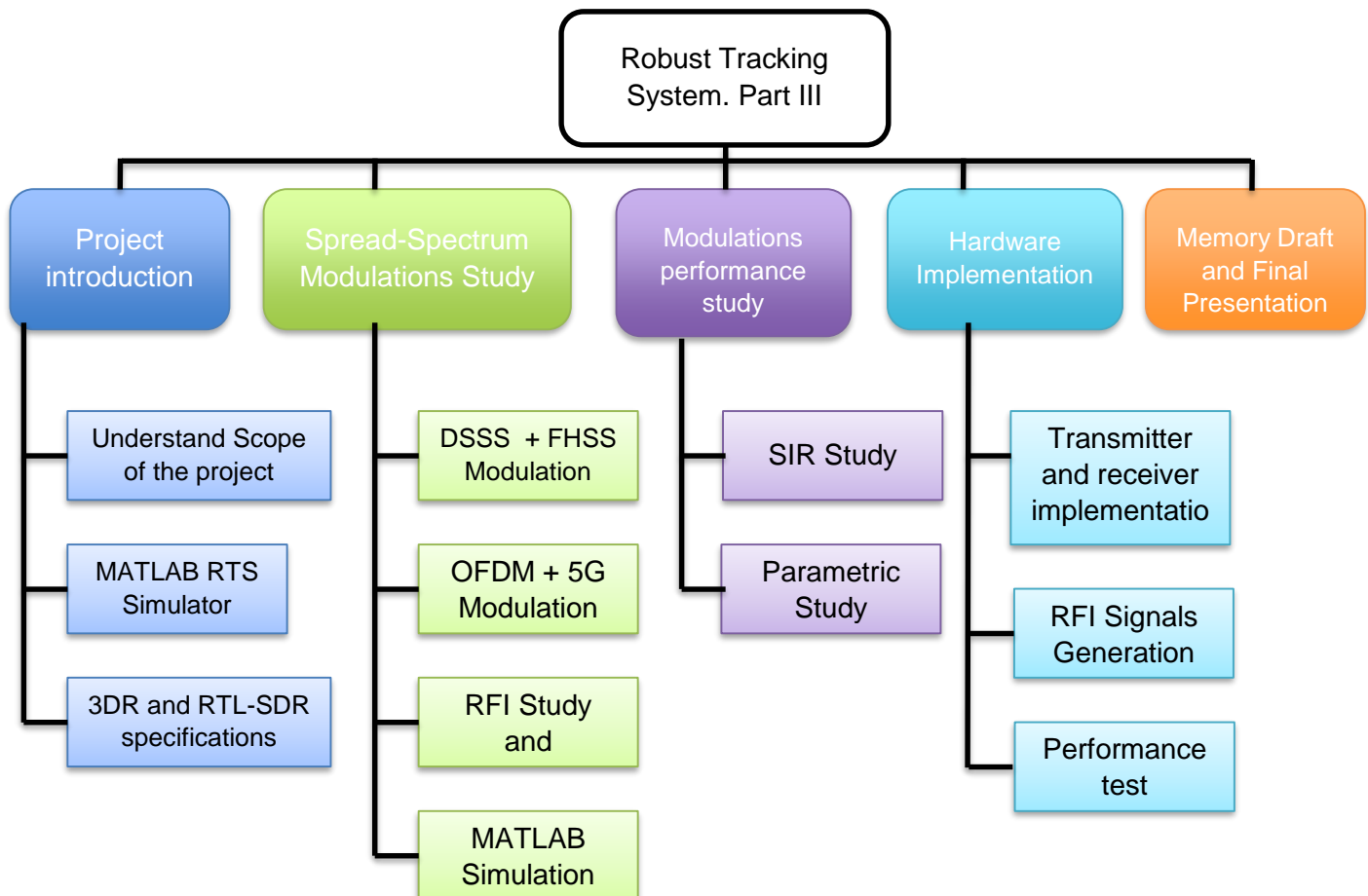
The project has been developed in the framework of one of the research lines carried out by Professor Adriano Camps at the RSLab, which is the detection and mitigation of RFI signals. In particular, the concept of the RTS is a part of the PhD. thesis of advisor Jorge Querol, and its first studies about RFI signals and their effects on GNSS devices will be taken into account during the development of the project.

The project is the continuation of two parts, Part I “Communications and hyperbolic navigation” and Part II “Transceivers and error estimation” developed by Dayal Kewalramani and Patrik James Cara Reyes respectively. This is the third, and last, part of the project and it will be using the transmitter already implemented in Part II and the communication between node and server implemented in Part I.

The final step of the project is to test the whole system together so all three parts will be attached and will work as one.

#### 1.5. Work packages, milestones and Gantt diagram

##### Work Breakdown Structure



## Work packages

Project: <b>Project Introduction</b>	WP ref: 1	
Major constituent: Preliminary work	Sheet 7 of 12	
Short description: Understand and learn all the project variables, requirements and specifications, the following steps to take and the previous simulations.	Planned start date: 10/11/2015 Planned end date: 28/02/2016	
	Start event: Meetings End event: MATLAB Simulation	
<b>Internal task T1:</b> Proposal Study. <b>Internal task T2:</b> System simulation using MATLAB. <b>Internal task T3:</b> Learn 3DR and RTL specifications and parameters.	Deliverables: Results	Dates:

Project: <b>Study and Simulation Spread Spectrum Modulations</b>	WP ref: 2	
Major constituent: Simulation	Sheet 8 of 12	
Short description: Study and Simulation the most used spread-spectrum modulations using MATLAB software.	Planned start date: 29/02/2016 Planned end date: 28/04/2016	
	Start event: Study End event: Simulation	
<b>Internal task T1:</b> Study DSSS, FH, OFDM modulations, a combination of the above and the 5G proposed modulations. <b>Internal task T2:</b> Study types of RFI signals. <b>Internal task T3:</b> Simulation in MATLAB.	Deliverables: MATLAB Simulations	Dates:

Project: <b>Signal-to-interference ratio (SIR) study</b>	WP ref: 3	
Major constituent: Simulation and results extraction	Sheet 8 of 12	
Short description: Study of the SIR at the output of the demodulator given the SIR at the input of it. Perform the study for each RFI signal and each simulated modulation.	Planned start date: 20/04/2016 Planned end date: 14/05/2016	
	Start event: Simulation End event: Conclusions	
<b>Internal task T1:</b> Montecarlo Simulation to study the SIR at the output of the Demodulator. <b>Internal task T2:</b> Parametric Study of the best simulation.	Deliverables:	Dates:

Project: <b>Hardware testing</b>	WP ref: 4	
Major constituent: Testing	Sheet 8 of 12	
Short description: Test the transmitter and receiver configuration using real signals and real radio frequency interference signals.	Planned start date: 30/04/2016 Planned end date: 23/06/2016	
	Start event: Configuration tx and rx. End event: Test results	
<b>Internal task T1:</b> Configure the transmitter (3DR) and receiver (RTL-SDR) to work with real signals. <b>Internal task T2:</b> Test the Tx and Rx	Deliverables: Test results	Dates:

Project: <b>RTS Validation.</b>	WP ref: 5	
Major constituent: Testing and Validation	Sheet 9 of 12	
Short description: Validation of the Reliable Tracking System (in collaboration with the project of the same title Part I & Part II) through laboratory and final field test in a real scenario.	Planned start date: 10/06/2016 Planned end date: 10/07/2016	
	Start event: Configuration End event: Testing results	
<b>Internal task T1:</b> Put together all the parts of the system and test the system in the laboratory. <b>Internal task T2:</b> Test the system in a real scenario	Deliverables: Test results	Dates:

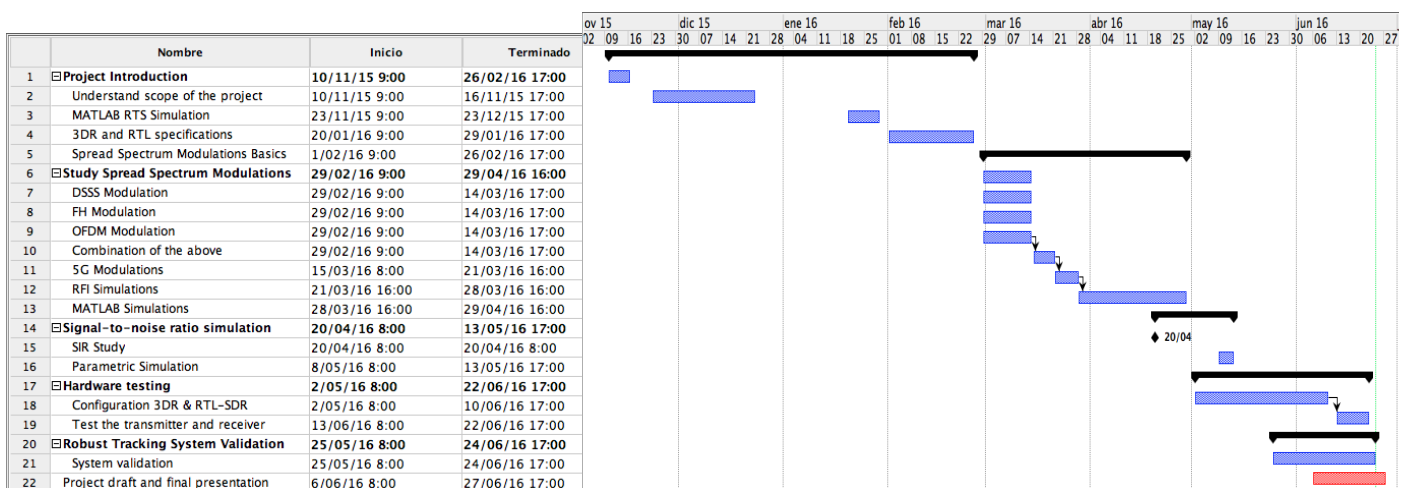
Project: <b>Project draft and final presentation</b>	WP ref: 6	
Major constituent: Writing	Sheet 9 of 12	
Short description: Write in the final document all the project and prepare the presentation.	Planned start date: 06/06/2016 Planned end date: 26/06/2016	
	Start event: Project writing End event: Final project	
	Deliverables:	Dates:



## Milestones

WP#	Task#	Short title	Milestone / deliverable	Date (week)
1	1	Proposal Study		
1	2	RTS in MATLAB	Simulate the basic RTS in MATLAB	20/12/2015
1	3	3DR and RTL	Learn about hardware specifications	20/02/2016
2	1	Spread Spectrum	Study DSSS, FH, CDMA and OFDM modulations	10/03/2016
2	2	RFI Signals	Study Radio Frequency Interference signals	10/03/2016
2	3	MATLAB Simulation	Simulation of each modulation and how an interference affects the result	28/04/2016
3	1	SIR Study and Parametric Study	Study of signal-to-interference ratio	07/05/2016
3	2	Extract Conclusions from SIR Study	Choose the best modulations	14/05/2016
4	1	Real Signals and 3DR/RTL-SDR	Configuration devices that can generate real signals	13/06/2016
4	2	Testing	Test results	23/06/2016
5	2	Lab testing	Real RTS testing	10/07/2016
6			Project Memory	23/06/2016

## Gantt Diagram



## 1.6. Deviation from the initial plan and incidences

### Incidences:

No major incidence interrupted the development of the work. However, the study and simulation of the spread spectrum modulations were slower than expected because of the introduction of new modulations to study. After a few weeks of studying DSSS, FH and OFDM modulations; a combination of them has shown up as a good approach in order to gain robustness against Radio-Frequency Interference (RFI) signals. Furthermore, the 5G proposed modulations also seemed other good options, so that, they were also taken into account. After a theoretical study, the 5G modulations were discarded due to the fact that they did not introduce any improvement to our system since they are focused on multi-user throughput increase by an efficient use of the spectrum, and also on enhancing weaker aspects of OFDM.

After the simulation of studied modulations, a Signal-to-Interference Ratio (SIR) study must be done in order to test the performance of each modulation at the output of the demodulator. This study is performed for each RFI signal and for a range of SIR at the input of the demodulator.

One minor incident we had was that the first transmitter we tried to use turned out to be broken and we needed to change it for another one. This small drawback cost a week work but we were able to recover the time lost.

The final step, attach the three parts of the project to test the whole system in a real scenario, proposed originally, could not be completed due to the fact that Part I and Part II did not finish their projects on time.

### Work plan modifications

The main Work Plan modifications are:

- Study and Simulation of the spread spectrum modulations deadline delayed to the 28th of April 2016
- New Work Package added: Signal-to-Interference Ratio study. A study of the SIR at the output of the demodulator.
- Deadlines delayed because of the delay of the first point listed here.

## **2. State of the art of the technology used or applied in this thesis:**

In this chapter, the background needed to understand the project and to start its development is presented.

### **2.1. Positioning / Tracking systems**

#### **2.1.1. GNSS**

The term Global Navigation Satellite System (GNSS) refers to a constellation of satellites providing signals from space transmitting positioning and timing data. By definition, a GNSS provides autonomous 3D positioning with global coverage. Nowadays, there are several functional systems, the most relevant are the Global Position System (GPS) from the United States (US), Galileo from European Union (EU) and GLONASS from Russia.

The tracking algorithm used by the RTS takes profit of GPS GGA NMEA messages to synchronize receivers' clocks. This process is essential for the RTS operation as it will be explained subsequently. Moreover, the NMEA sentence is also used to, optionally, find the receivers position, even though they can have fixed positions.

The GPS project was developed by the US Government in 1973 to overcome positioning systems predecessors. GPS constellation is formed by 32 satellites in a Medium Earth Orbit (MEO) guaranteeing 5 satellites in line of sight at any location. GPS only requires 4 satellites to determine 3D positioning and timing, but more of them are recommended in order to increase the positioning precision. The data format standard used is the National Marine Electronics Association (NMEA) and it is supported by all GPS manufacturers [11].

#### **2.1.2. Terrestrial systems**

Among the last 20 years there has been an effort to develop positioning systems independent of, and complementary to Global Navigation Satellite Systems (GNSS). An outstanding example is the case of eLoran, an enhanced version of Loran system, built with nowadays technology, which improves its old version in accuracy, availability, and reliability. eLoran is a low frequency system (P-band) that uses terrestrial-based stations to provide users accurate all-weather Position, Navigation, Timing, and Data (PNT&D) services, using hyperbolic navigation as its predecessor.

Hyperbolic navigation refers to a class of navigation systems based on the difference in timing between the receptions of two signals, without reference to a common clock (as in GNSS). This timing reveals the difference in distance from the receiver to the two stations. Plotting all of the potential locations of the receiver for the measured delay produces a series of hyperbolic curves. Taking the intersection of two of such hyperbolic curves reveals the receiver's location.

The RTS uses at least 3 receivers with known position to estimate the transmitter position. On the other hand, Time of Arrival (TOA) (time that takes the signal to travel from transmitter to receiver) is needed to retrieve the distances and solve hyperbolic navigation equations.

The Least-Mean-Square algorithm (LMS) is used in adaptive filters to find the filter coefficients that allow to obtain the minimum expected value of the square of the error signal, defined as the difference between the desired signal and signal produced at the output of the filter. It belongs to the family of the stochastic gradient algorithms, i.e., the filter is adapted based on the error in the current time only. It was invented by a professor of Stanford University named Bernard Widrow and his first doctoral student, Ted Hoff in 1960. Its importance is that it is a very simple algorithm. In the RTS, LMS algorithm is used to solve hyperbolic equations and to retrieve the tracked transmitter position.

## 2.2. Spread Spectrum Modulations

A spread-spectrum signal is one that has an extra modulation that expands the signal bandwidth beyond what is required by the underlying data modulation. Spread-spectrum communication systems are useful for suppressing interference, making interception difficult, accommodating fading and multipath channels, and providing a multiple-access capability.

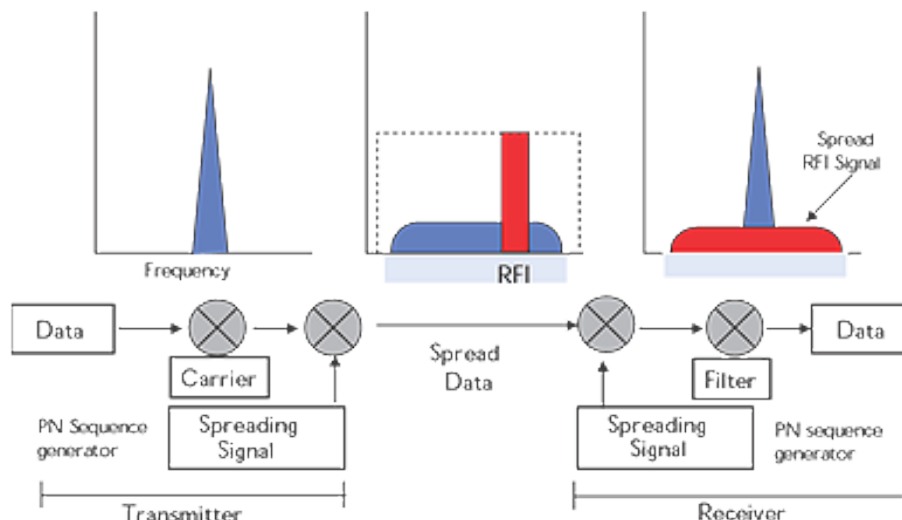


Figure 1: Basic diagram of a Spread-spectrum modulation system and its functioning

### 2.2.1. Direct-Sequence Spread Spectrum

In Direct-Sequence Spread-Spectrum (DSSS), the message signal is used to modulate a bit sequence known as the Pseudo-Random Noise (PRN) code. This PRN code consists of pulses of a much shorter duration (larger bandwidth) than the pulse duration of the message signal, therefore the modulation results in a signal that has a bandwidth nearly as large as that of the PRN sequence. In this context, the duration of the PRN pulses is referred to as chip duration, and the smaller this value, the larger the bandwidth of the resultant DSSS signal, and the more robust to RFI the resultant signal becomes.

The receiver must be set to the same PRN code and must listen to the incoming signal at the right time in order to properly receive and demodulate the signal.

### 2.2.2. Frequency Hopping Spread Spectrum

Frequency-Hopping Spread-Spectrum (FHSS) is a technique where the data signal is modulated with a narrowband carrier signal that "hops" in a random but predictable sequence from frequency to frequency as a function of time over a wide frequency band. The signal energy is spread in the time domain rather than chopping each bit into small pieces in the frequency domain. This technique reduces interference because a signal from a narrowband system will only affect the spread spectrum signal if both are transmitting at the same frequency at the same time. If synchronized properly, a single logical channel is maintained.

The transmission frequencies are determined by a spreading, or hopping, code. The receiver must be set to the same hopping code and must listen to the incoming signal at the right time and correct frequency in order to properly receive the signal.

### 2.2.3. Orthogonal frequency-division multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) is a digital multi-carrier modulation scheme that extends the concept of single subcarrier modulation by using multiple subcarriers within the same single channel. Rather than transmit a high-rate stream of data with a single subcarrier, OFDM makes use of a large number of closely spaced orthogonal subcarriers that are transmitted in parallel. Each subcarrier is modulated with a conventional digital modulation scheme (such as QPSK, 16QAM, etc.) at low symbol rate. However, the combination of many subcarriers enables data rates similar to conventional single-carrier modulation schemes within equivalent bandwidths.

### 2.2.4. 5G Modulations

Although OFDM has been a great success and still has many advantages, there are many ideas for new 5G waveforms that could bring additional advantages to the new cellular system under certain conditions and circumstances. No single waveform provides all the advantages and answers that are needed but four of them will be studied in order to determine if they provide an improvement to our system.

This four 5G techniques are focused on improving the OFDM main limitations that are:

- Tailored services to different needs and channel characteristics.
- Reduced out-of-band emission (OOBE).
- Extra tolerance to time-frequency misalignment.
- Low spectral efficiency due to the introduction of the Cyclic Prefix.

In this project, the four 5G modulations that will be studied are:

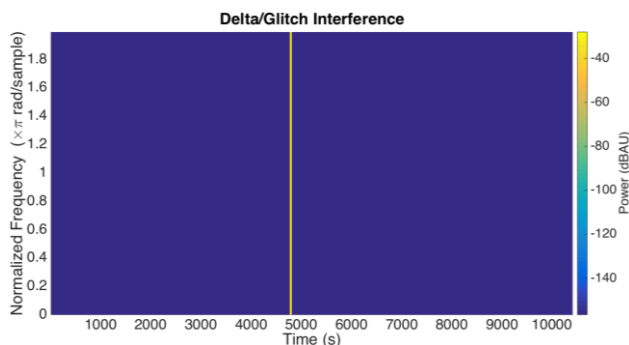
- filtered-Orthogonal Frequency-Division Multiplexing (f-OFDM)
- Generalized Frequency-Division Multiplexing (GFDM)
- Filter Bank Multi-Carrier (FBMC)
- Universal Filtered Multi-Carrier (UFMC)

The main goal of these modulations, as it was mentioned before, is to overcome the main weakest points of the OFDM. The spread-spectrum modulations and the advantages of each 5G modulation will be explained in more detail in Appendix 1.

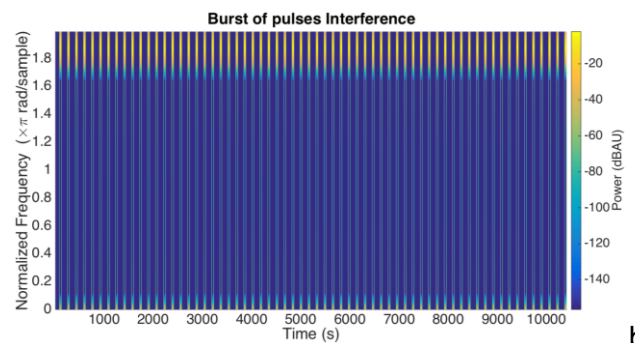
### 2.3. Radio-Frequency Interference Signals

Radio-Frequency Interference (RFI) signals are disturbances that affect any nearby electrical circuit due to either electromagnetic induction or electromagnetic radiation emitted from either an external or internal source. The origin of RFI signals may be of intentional or unintentional nature. Most common unintentional sources are spurious or harmonic signals of lower frequency bands, inter-modulation products, broadband signals overlapping reserved bands of operation, and out-of-band emissions. Moreover, RFI signals may be intentionally used for radio jamming, as in some forms of electronic warfare, threatening the integrity of applications based on RF devices. From several studies (e.g. [17]), it emerges that most of commercial jammers usually employ linear frequency modulated signals (i.e. chirp signals) which sweeps in a range of several megahertz in a few microseconds affecting the entire band targeted by the device. In this project six types of radio frequency interference signals are studied:

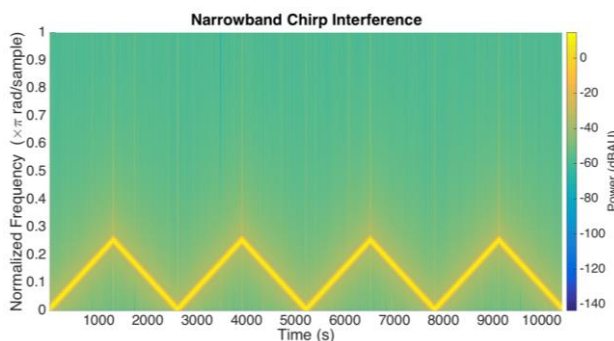
- **Delta / Glitch RFI signal:** this is a very narrow signal in the time domain which has a large bandwidth and therefore, it occupies the entire spectrum during the short time in which is present.
- **Burst of pulses RFI signal:** this signal is constructed by repeating with a high frequency a basic pulse.
- **Wideband / Narrowband Chirp RFI signal:** a chirp is a signal in which the frequency increases (up-chirp) or decreases (down-chirp) with time.
- **Narrowband / CW RFI signal:** a continuous waveform (CW) is an electromagnetic wave of constant amplitude and frequency; e.g. a sine wave.
- **Wideband RFI signal:** a wideband signal, present in all frequencies. It is probably the most problematic type of interference for the system



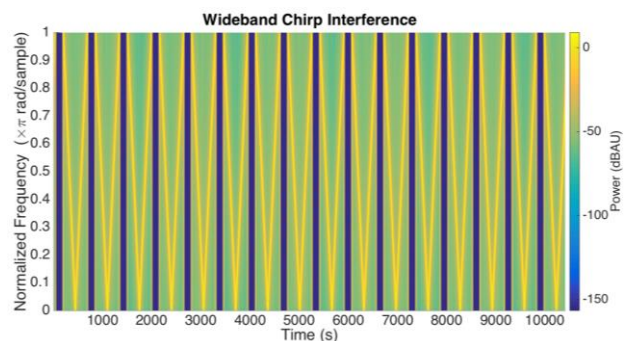
a)



b)

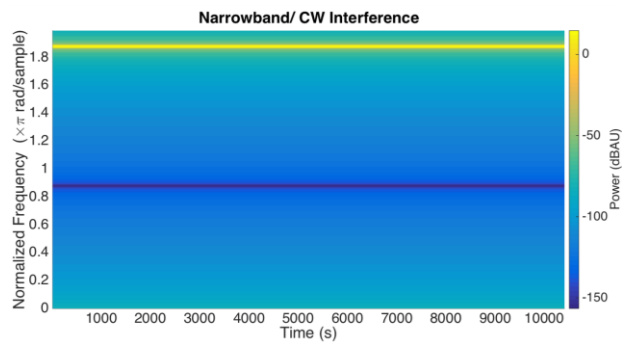


c)

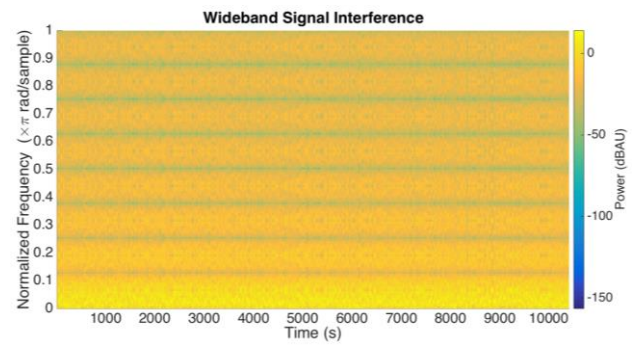


d)





e)



f)

Figure 2: Spectrum of the six types of Radio Frequency Interference: a) Delta/Glitch signal; b) Burst of Pulses; c) Narrowband Chirp; d) Wideband Chirp; e) Continuous Wave and f) Wideband signal

### 3. System Simulation:

In the following section a simulation of the whole system is done in order to study the effect of the modulations and Radio Frequency Interference (RFI) signals on the system. The section is split in two parts; the first one will explain the Graphic User Interface (GUI) created in order to simulate the system while the second one will explain in more detail every step followed in the simulations of the different spread-spectrum modulations.

#### 3.1. Robust Tracking System Simulator

The main goal of this section is to test the performance of our Robust Tracking System in a simulated scenario where the parameters of the simulation can be changed in order to test different scenarios with different conditions. In order to simulate the whole system, the modulation simulator will be attached to the part corresponding to the hyperbolic navigation and the Least Mean Squares algorithm simulation. Hence, the results from [9] have been merged with the use of the spread-spectrum modulations.

A Graphic User Interface (GUI) has been created in order to set the parameters for the simulation and to see the results in a visual and interactive way. Figure 3 shows the first interface where the simulator asks for the required parameters. These are the following:

- Transmitter power (dB)
- LMS algorithm parameters:
  - Number of receivers
  - Number of iterations
  - Error Value
  - Step-size for LMS algorithm( $\mu$ )
- Environment selection
  - Rural environment (no buildings nor constructions taken into account)
  - Urban environment (buildings and constructions taken into account)
- Modulation choice
- Radio-Frequency Interference (RFI) signal choice
- Signal-to-Interference Ratio (SIR) (dB)

The screenshot shows a window titled 'receivers\_pos' with the text 'Please, enter simulation parameters'. The window is divided into several sections:

- Tx\_side**: A text input field for 'Transmitter Power (dBm)' with the value '20'.
- Simulation Options**:
  - 'Number of receivers': input field with '4'.
  - 'Error': input field with '0.5'.
  - 'Number of iterations': input field with '20'.
  - ' $\mu$ ': input field with '0.2'.
  - 'Transmitter in movement': radio buttons for 'Yes' (selected) and 'No'.
- Environment**:
  - 'Open Space (no buildings or constructions around)': radio button (selected).
  - 'Urban environment (Buildings and constructions taken into account)': radio button.
  - 'Flat Earth': radio button (selected).
  - 'Okumura-Hata': radio button.
- Signal modulation**:
  - 'Direct-Sequence Spread Spectrum': checkbox (unchecked).
  - 'Frequency Hopping': checkbox (checked).
  - 'Orthogonal Frequency Division Multiplexing': checkbox (unchecked).
  - 'DSSS + FH': checkbox (unchecked).
- RFI Signal**:
  - 'Delta / Glitch': checkbox (checked).
  - 'Burst of pulses': checkbox (unchecked).
  - 'Narrowband Chirp': checkbox (unchecked).
  - 'Wideband Chirp': checkbox (unchecked).
  - 'Narrowband Signal': checkbox (unchecked).
  - 'Wideband Signal': checkbox (unchecked).
- RFI Power**:
  - 'SIR in (dB)': input field with '0'.

At the bottom left, there is a 'Next Screen' button.

Figure 3: Interface where the user chooses the simulation parameters



Once the user has introduced all the parameters, it can proceed to the simulation as it can be seen in Figure 4.

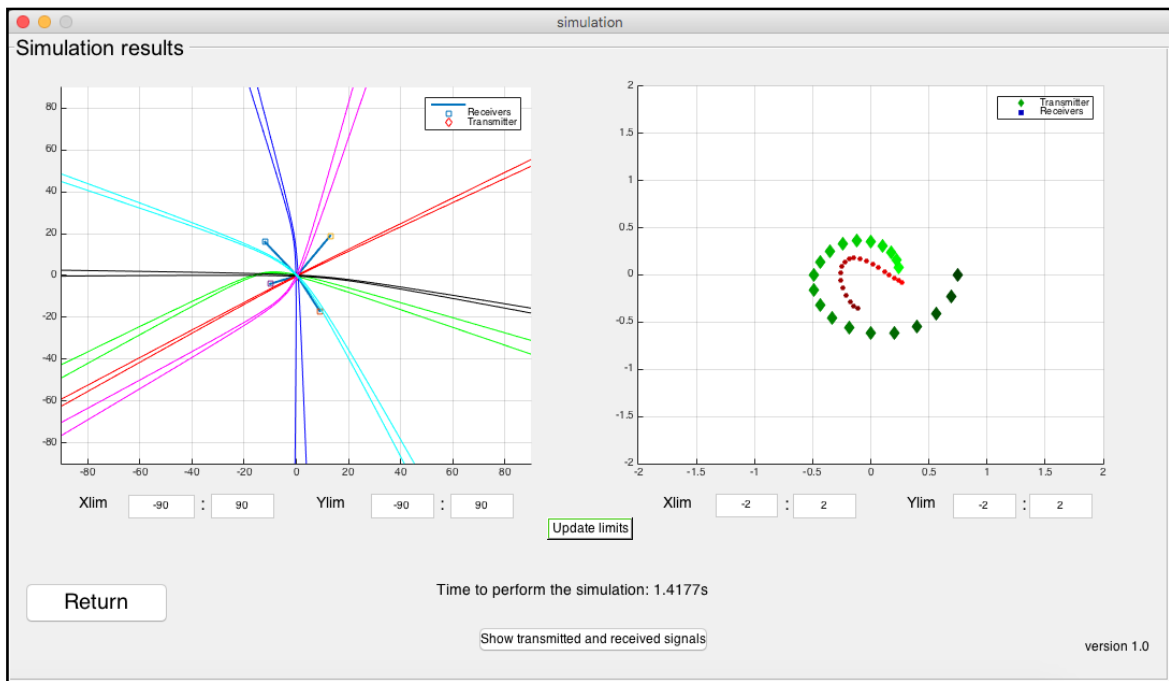


Figure 4: Interface that shows the simulation results

Regarding Figure 4, in the plot on the left it can be seen the hyperbolic navigation plot (the hyperbolas intersecting on the transmitter spot). Hyperbolas, corresponding to the TDOA technique used in the RTS to compute the transmitter position and explained in the state of the art, are shown. These hyperbolas intersect, with more or less accuracy, in one point, the transmitter position.

The plot on the right shows the LMS algorithm simulation, where it can be observed how the transmitter position is estimated in each iteration. This estimation has taken into account the modulation and the RFI type selected. It also takes into account the Signal-to-Interference Ratio (SIR) specified in the previous step. If a poor SIR is set, the estimation of the transmitter position by the LMS algorithm gets worse introducing a significant error and therefore, causing an inaccurate estimation.

It must be said that four boxes per figure appear in the interface in order to allow the user to change the span of the plots since in a GUI the user cannot use the plot tools such as zoom in or zoom out. The simulation time is also shown on the centre of the interface.

After the simulation has been done the user can view the signals that have been part of it. For this reason, two more interfaces have been created, the first one will show the signals on the transmitter side and the other one will show the signals on the receiver side. These interfaces will be shown in the Appendix 2. The signals that appear on those interfaces are extracted from the simulation and they are practically equal to the ones explained in section 3.2 where an exhaustive description of every step of the simulation of the proposed

modulations is done. The comparison between a good estimation with good SIR and a bad estimation with poor SIR is shown in the Appendix 2 as well.

With this GUI, a simulation as close to reality as possible is implemented so it can provide results of the performance of the system closer to the ones that would be obtained in a real scenario.

### 3.2. Modulations Simulation

After a theoretical study of the advantages the spread-spectrum modulations, presented in the state of the art, would introduce to our system, only Direct-Sequence Spread-Spectrum (DSSS), Frequency Hopping (FH), DSSS + FH and Orthogonal Frequency-Division Multiplexing (OFDM) have been chosen to be simulated in the system simulator exposed on 3.1. These modulations have some interesting features that make them ideal for our interests and, therefore, worth of being simulated. On the other hand, the 5G modulations have been discarded due to the fact that they are focused on the improvement of the weakest aspects of OFDM as explained before and, therefore, they would not introduce any improvement, compared with OFDM, to our system.

Given that we want to examine the performance of the modulations in front of RFI signals at the input of the demodulator, we have set the signal-to-noise ratio (SNR) at a high value ( $> 60$  dB) so that thermal noise power does not interfere in these results.

The main purpose of these simulations is to study the behaviour of the chosen spread-spectrum modulations in front of RFI signals. A step-by-step simulation must be done, choosing accurately all the parameters to get the results as close to the reality as possible. The steps every simulation follows are described in the next six points:

- Definition of the basic signal to modulate.
- Definition of the chosen spreading form or spreading forms.
- Modulation of the basic signal
- Simulation of the delay introduced by the travel of the signal.
- Definition and addition of the Gaussian noise and the RFI signal.
- Synchronization and demodulation of the received signal.

In every modulation simulated the original signal is a pulsed signal. This is 8 bits, four 1s and four -1s to be modulated.

The most explanatory signal figures will be shown in the following sections in order to better understand how the modulation and demodulation of the signal has been done.

### 3.2.1. Direct-Sequence Spread Spectrum Simulation

To simulate the direct-sequence spread spectrum modulation; first of all, a basic signal to be modulated is defined. As it mentioned before, this signal is an 8 bits pulsed signal designed with a sample rate equal to 2048 samples per bit.

After that, the pseudo-random noise sequence is defined using two linear feedback shift registers (LFSR) combined by the logical operation XOR. The spreading signal sequence is designed with 512 chips and a sample rate equal to 4 samples per chip. Once the PRN has been defined the following step is to combine the previous two signals in order to achieve the spread spectrum signal. In Figure 5 the PRN sequence and the final modulated signal are shown.

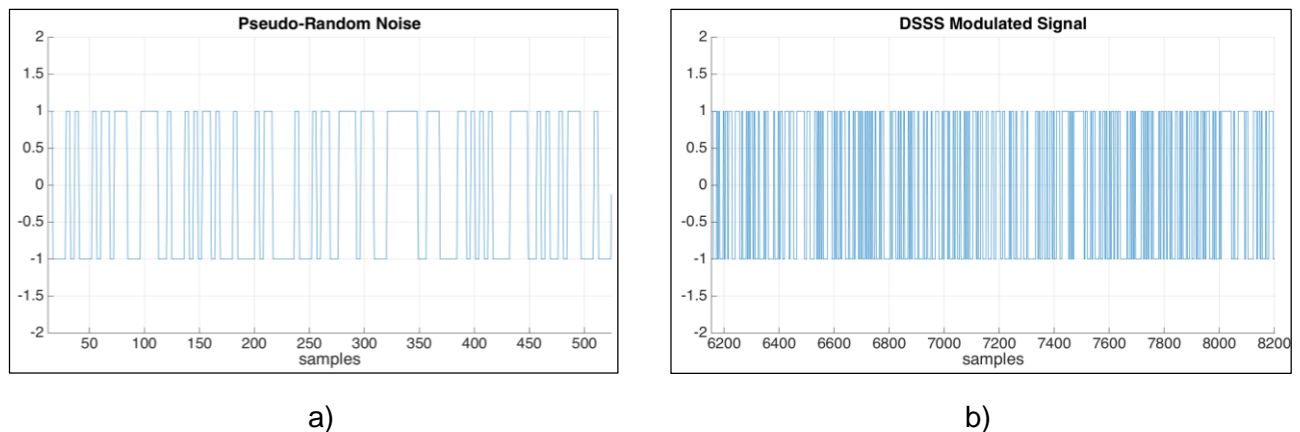


Figure 5: a) Pseudo-Random Noise; b) Signal after the spreading has been done

The modulated signal, as it can be seen in Figure 5, has much shorter pulses than the original signal and consequently it has a much larger bandwidth in the frequency domain. This feature makes this modulation robust in front of RFI signals.

Up to this point, every signal corresponding to the transmitter side has been defined and designed with the parameters explained before. After that, the channel simulation must take place.

To simulate the effect of the channel over the signal transmitted, a random delay, simulating the time the signal is travelling from transmitter to receiver, must be introduced. In this step, Gaussian noise is added to the transmitted signal and the RFI signal is introduced as well, simulating another device transmitting it in the same frequency band.

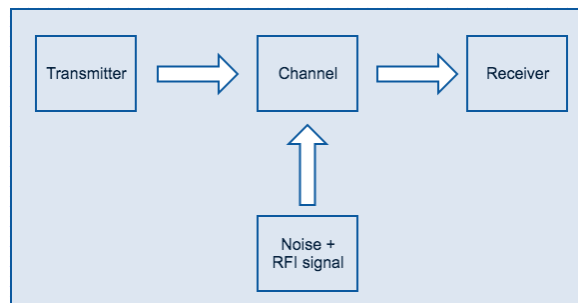


Figure 6: Block diagram of the path and the signals involved in the modulation

The signal the receivers get is shown in the Figure 7.

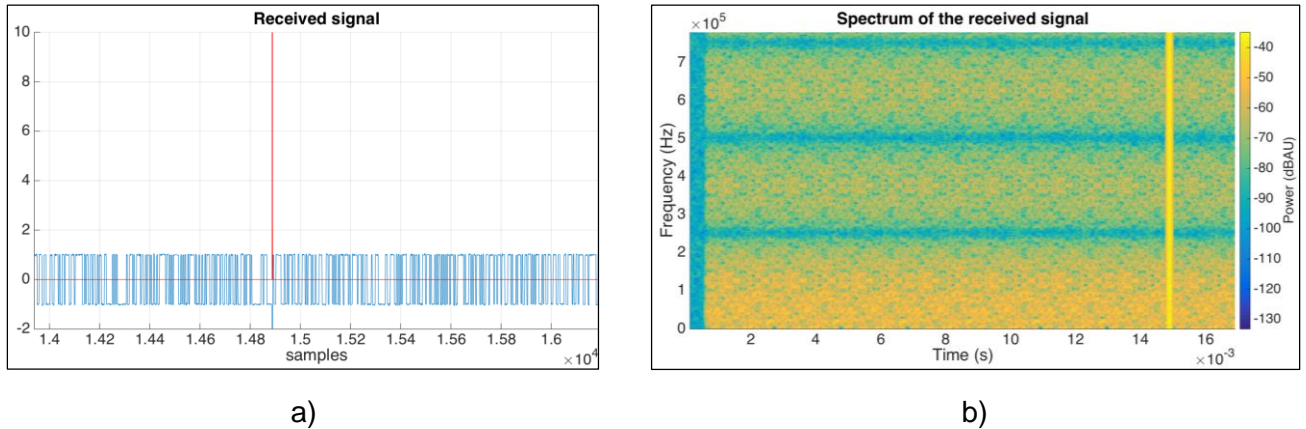


Figure 7: a) Zoom of the received signal with the RFI; b) Spectrum of the received signal

The RFI signal, in this simulation, is a delta interference signal (in red). In every simulation the position and the phase of the RFI signal are random in order to achieve a result closer to the reality. In Figure 7b, it can be seen that the whole spectrum is occupied by the modulation and the delta interference can also be seen as a short time signal present in all the frequencies.

Once the signal is received the demodulation takes part. To sync up the signal, it is correlated with the pseudo-random sequence used to modulate the signal.

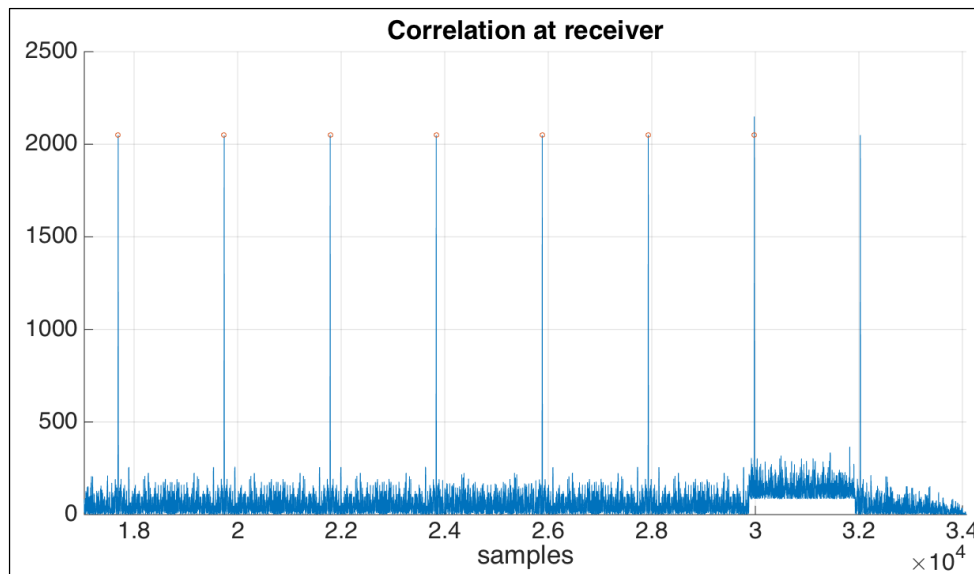


Figure 8: Correlation of the DSSS signal with the PRN at the receiver

As it is depicted in Figure 8, eight correlation peaks are found to correspond to the 8 bits transmitted before. The perturbation observed between samples  $3 \times 10^4$  and  $3.2 \times 10^4$  corresponds to the effect of the RFI signal which is minimal.

Finally, the original signal is demodulated and the receiver sends the relative Time of Arrival (TOA) to the server in order to compute the transmitter position. If the signal received is not the one sent by the transmitter, after the demodulation, the signal is discarded.

### 3.2.2. Frequency Hopping Simulation

To simulate the Frequency Hopping Spread-Spectrum (FHSS) modulation; first of all, a basic signal to be modulated is defined. This signal, as in the case of DSSS, is an 8 bits pulsed signal designed with a sample rate equal to 2048 samples per bit.

After that, the subcarriers that will be used in the modulation are defined and a hopping pattern is set randomly. In this simulation, 8 subcarriers have been used at a sample rate equal to 256 sample per carrier, each with a different frequency that will modulate the original signal and will spread its bandwidth. Once the hopping pattern has been defined the following step is to combine the previous two signals in order to achieve the spread spectrum signal. In Figure 9 the hopping pattern sequence and the final modulated signal are shown.

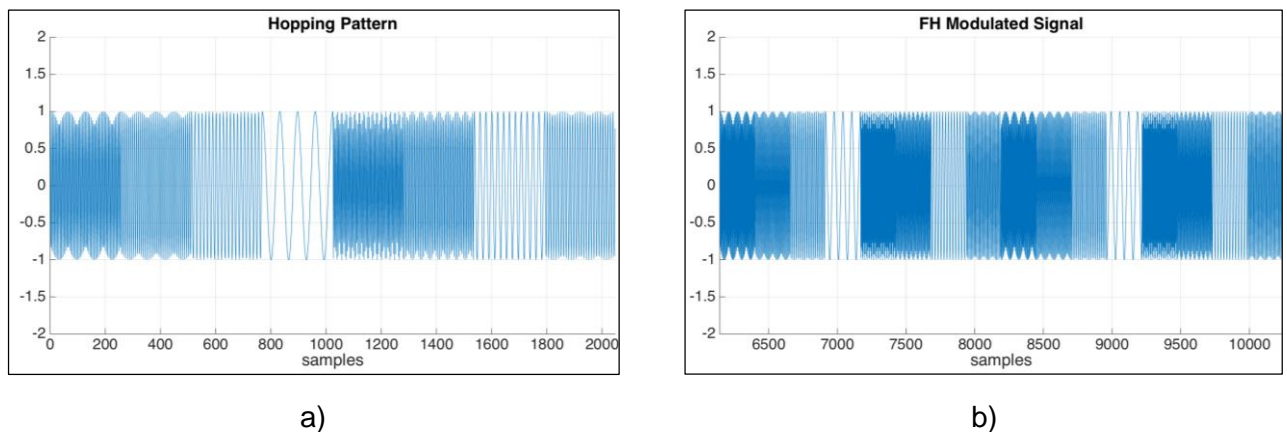


Figure 9: a) Hopping pattern used in the modulation; b) Zoom of the FHSS signal to transmit

The modulated signal, as it can be seen Figure 9b, has been distributed evenly between the eight subcarriers and consequently it has a much larger bandwidth in the frequency domain. This signal should have a constant amplitude but, because of the numbers of points used to create each subcarrier the surrounding is not constant.

The point that makes this modulation extremely robust in front of narrowband RFI signals, as it was mentioned before, is because any narrowband interference signal will only affect the performance of some subcarriers leaving the other uncorrupted and thus the data they are transmitting will remain unchanged.

The following step, once the transmitted signal has been defined, is to simulate the effect of the channel. In order to get a channel simulation as close to the reality as possible a random delay is introduced simulating the travel of the wave from the transmitter to the receiver position. Furthermore, an Additive White Gaussian Noise is added to the signal and the RFI signal is introduced as well.

The RFI signal is chosen from a pool of 6 options which are the ones mentioned in the state of the art: Glitch; Burst of pulses; Narrowband and Wideband Chirp; and Narrowband and Wideband Signal.

The received signal is shown in Figure 10:

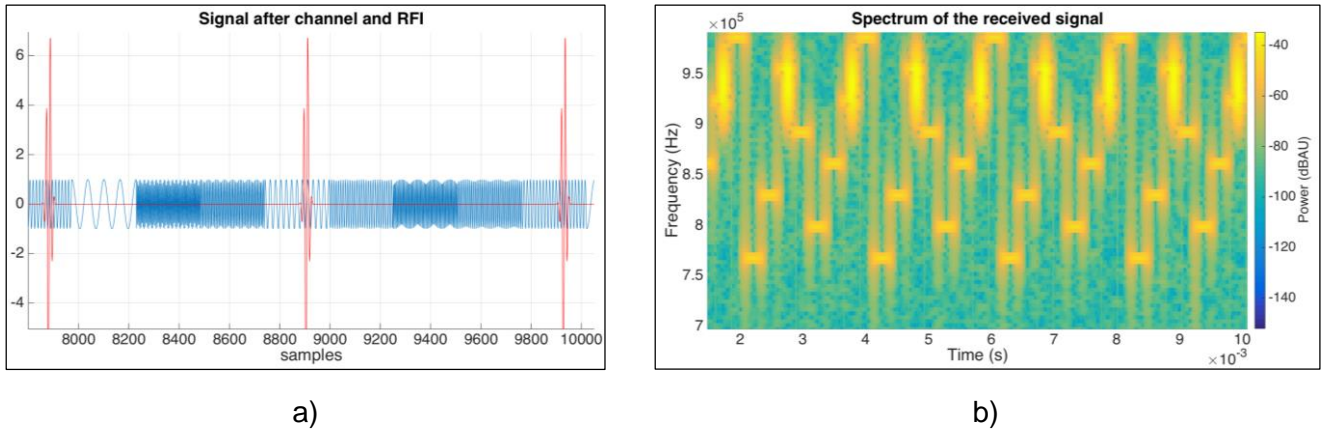


Figure 10: a) Received signal with RFI; b) Spectrum of the signal at the receiver

The RFI signal, in this simulation, is a burst of pulses interference signal (in red). In every simulation the position and the phase of the RFI signal are random in order to achieve a result closer to the reality. In the spectrogram it can be seen that the hopping pattern through the eight subcarriers and it can be seen the burst of pulses as well (top of the figure)

Once the signal is received, the demodulation takes part. To sync up the signal, it is correlated with the hopping pattern used to modulate the signal.

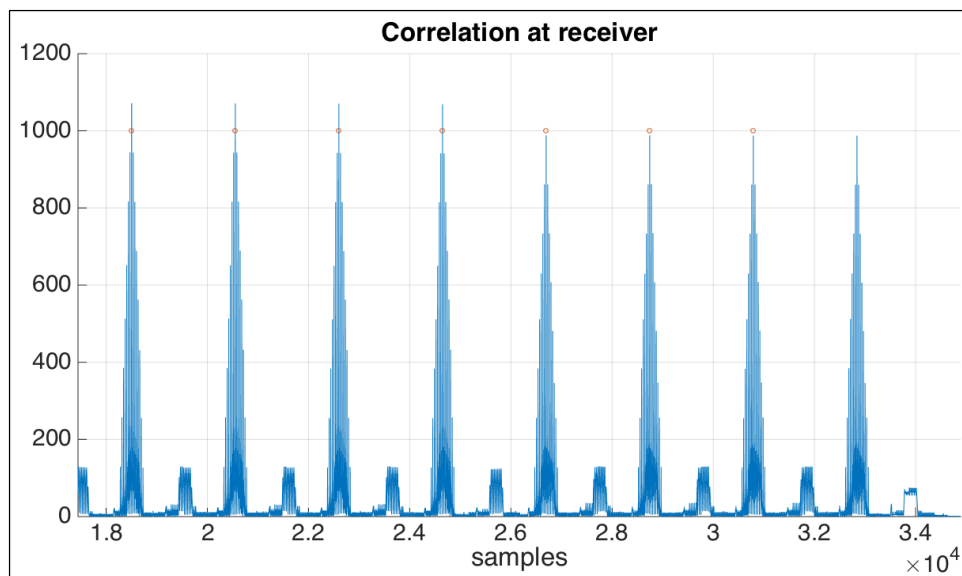


Figure 11: Correlation of the signal with the hopping pattern at the receiver

In the Figure 11, eight peaks can be seen corresponding to the 8 bits transmitted before. They are positive because the plotted signal is the correlation squared, which is equal to the power at the output of the correlator.

Finally, the original signal is demodulated and the receiver sends the relative time of arrival to the server in order to compute the transmitter position.



### 3.2.3. Orthogonal Frequency-division Multiplexing Simulation

To simulate the orthogonal frequency-division multiplexing modulation five m-files have been written to develop this MATLAB program. One of them is the main program script file, which is the only file that needs to be run, while other m-files will be invoked accordingly.

First of all, a basic signal to be modulated is defined. This signal, as in the other two simulations, is an 8 bits pulsed signal designed with a sample rate equal to 2048 samples per bit. After that, the subcarriers that will be used in the modulation are defined and the input signal is divided through a process of conversion from serial to parallel and a portion is assigned to each subcarrier.

The next step is to modulate the signal using the Differential Phase Shift Keying (DPSK) modulation, a form of digital modulation, where the binary input information is comprised of the difference between two successive stages of signalling elements, and not the absolute phase. It is considered a non-coherent form of PSK and therefore in reception the need for a coherent reference signal for recovering the carrier signal is avoided.

Afterwards, the transmitter applies the Inverse Fast Fourier Transform (IFFT) to the resulting signal in order to have all the carriers transmitting in parallel to fully occupy the available frequency bandwidth. Finally, a cyclic prefix is added to add robustness against inter-symbol interference and to make easier the synchronization part at the receiver.

The Figure 12 shows the transmitted signal:

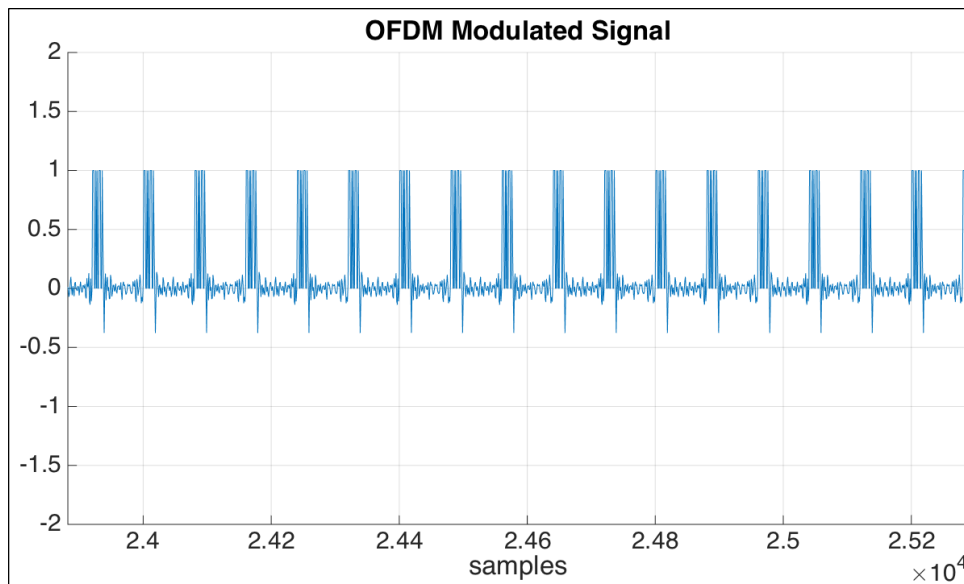


Figure 12: Signal, after the OFDM modulation, which will be transmitted

After simulating the transmitter side the channel path is taken into account. As it has been done with the other simulations, a random delay is introduced simulating the time the signal is traveling from the transmitter to the receivers. In this step there are also introduced the Gaussian noise and the RFI signal.

After the channel, the signal the receivers capture is the one in Figure 13:

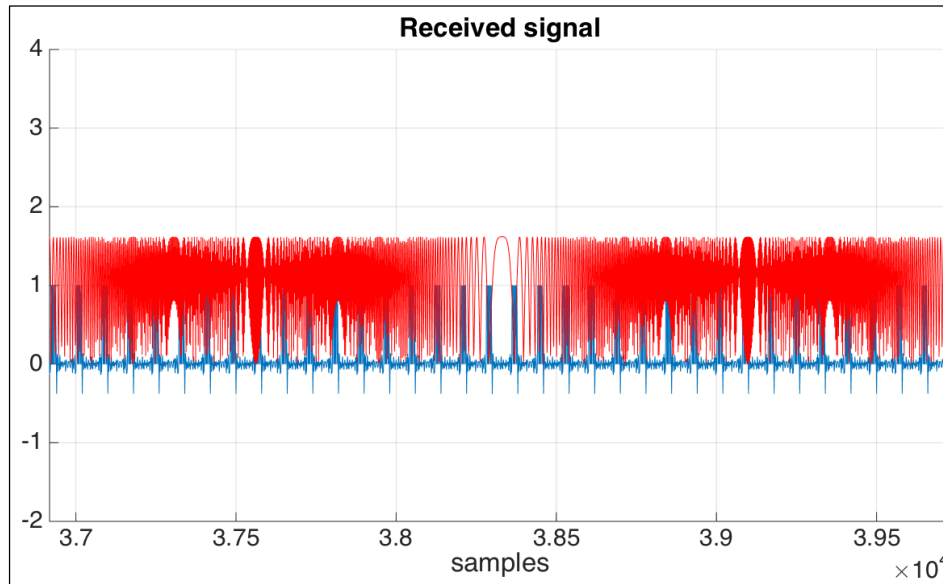


Figure 13: Signal with the RFI received

As it can be seen a strong RFI signal is showed in this simulation. It is the case of a wideband chirp, which disturbs all the subcarriers and thus the demodulation is more complicated.

Once the signal has been received, the synchronization is performed by calculating the correlation between the signal and the known cyclic prefix added at the transmitter. After that, the signal is transformed using the Fast Fourier Transform (FFT) and demodulated using the DPSK demodulation.

Finally, the data is put together by the parallel to serial converter and the demodulated signal takes the form of the original signal.



### 3.2.4. DSSS + FH Simulation

The idea of this modulation is to first spread the signal using the direct-sequence spread spectrum modulation and perform, afterwards, a frequency hopping in order to try to gain robustness in front of interferences. As the three simulations before, first of all, a basic signal to be modulated has to be defined. This signal is designed with a sample rate equal to 16384 samples per bit in order to be able to perform the two modulations.

After that, the pseudo-random sequence is defined using two linear feedback shift registers combined by the logical operation XOR, as it was done in the DSSS modulation.

In this case, the pseudo-random sequence is designed with 32 chips and a sample rate equal to 512 samples per chip. Once the signal has been modulated using the pseudo-random sequence described above, the subcarriers that will be used to perform the FHSS modulation are defined and a hopping pattern is set randomly.

Figure 14 shows the PRN and the hopping pattern used in this simulation:

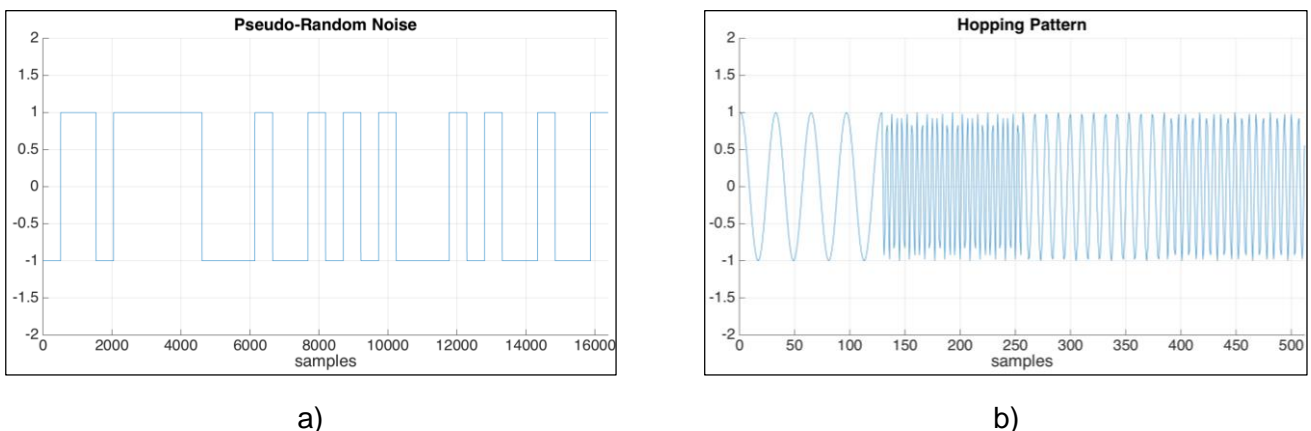


Figure 14: a) Pseudo-Random Noise and b) Hopping Pattern used in the modulation

In this simulation 4 subcarriers have been set at a sample rate equal to 512 samples per carrier, each with a different frequency that will modulate the original signal and will spread its bandwidth. The following step is to combine the previous two signals in order to achieve the DSSS+FH spread spectrum signal.

Once the original signal has been modulated, a random delay, simulating the delay introduced by the travel of the signal from transmitter to receiver, is introduced. The Gaussian noise and the interference are introduced in this step, as well.

The signal the receivers get is shown in Figure 15.

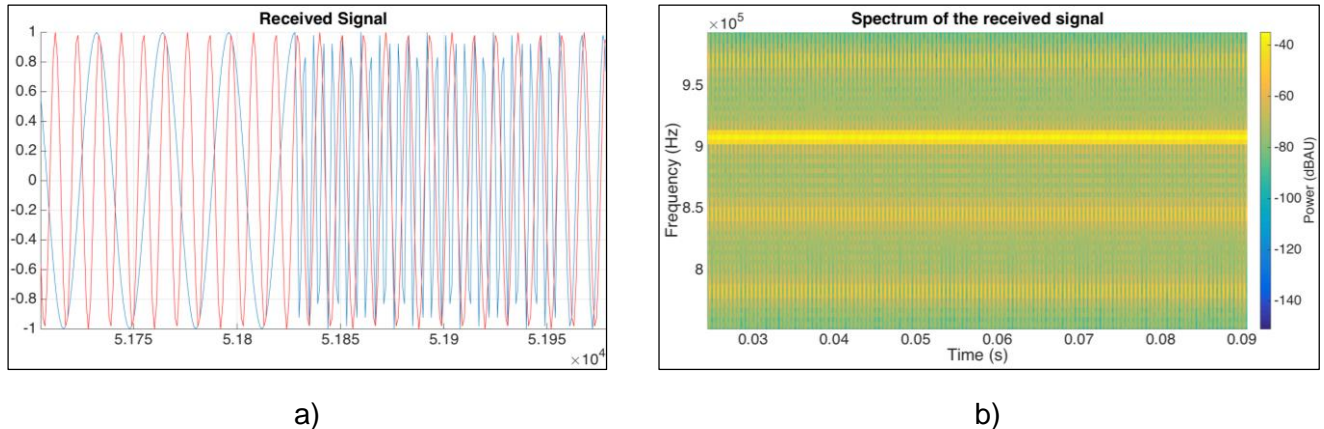


Figure 15: a) Signal with RFI signal at the receiver; b) Spectrum of the received signal

The RFI signal, in this simulation, is a narrowband CW interference signal (in red). In Figure 15a, in blue, the transmitted signal affected only by the Gaussian noise and, in red, the continuous wave RFI signal present among the entire time can be observed. In Figure 15b it can be easily seen the RFI signal and it also can be seen that it corrupts only a subcarrier due to the fact that is a narrowband signal interference centred in that subcarrier. The other three subcarriers will deliver the modulated data uncorrupted to the receivers.

Once the signal is received the demodulation takes part. To sync up the signal, it is correlated with the hopping pattern used to modulate the signal. This step is the same as in the individual Frequency Hopping Spread Spectrum simulation, the received signal is correlated with the known hopping pattern and the peaks of this operation are taken to demodulate the signal. After this step, the resulting signal is correlated with the pseudo-random sequence used in the transmitter in order to proceed with the second demodulation. This step, as it was the last one, it is the same as in the individual Direct-Sequence Spread Spectrum simulation. In this case the reason to do the correlation is not to synchronize the signal but to check if there were any errors on the first demodulation. In this sense, this step adds a degree of robustness to the spread-spectrum modulation.

Finally, after the two demodulations, the original signal is recovered and the time of arrival is sent to the server in order to compute the transmitter position.

## 4. Performance Simulation

The second part of the project is explained in the following section. First, a study of the performance of the simulated modulations in front of RFI signals is done in order to select the best modulation for our system. Second, a parametric study of the chosen modulation is performed to adjust the modulation parameters, in the best way, to our needs.

### 4.1. Signal-to-Interference Ratio Study

One of the simulated modulations, or a combination of them, will be implemented with the available hardware in order to test its performance with real signals. In order to choose the best modulation a study has been performed.

To understand better, the scope of the study, a sketch of the setup is shown in Figure 16.

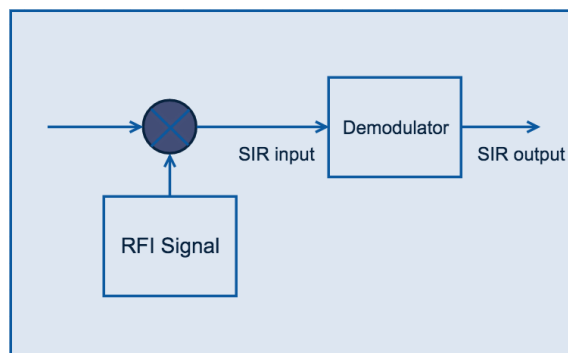


Figure 16: Diagram explaining the setup used in the study

The main goal of the study is to compute the Signal-to-Interference Ratio (SIR) at the output of the demodulator with a given SIR at its input. This study will be done for every modulation and for every Radio-Frequency Interference (RFI) signal proposed in Section 2.

As the position and the phase of the RFI signals are randomly set, it will be needed to execute as many simulations as possible in order to contemplate the maximum cases possible. To do that 500 simulations will be executed for every SIR value at the input of the demodulator. A range from -30dB to 30dB will be considered as the possible values of the SIR at the input of the demodulator. Once all the simulations have been performed the percentile 95 will be computed of all the simulations.

The results will be plot in a graph in which the vertical axis represents the SIR at the output and the horizontal axis represent the SIR at the input, both in dB as shown in Figure 19. In every plot the 1:1 function will be displayed in order to see how the modulations are working. If the results are below the 1:1 function, the demodulator will be introducing its own error and will be hindering the received signal.

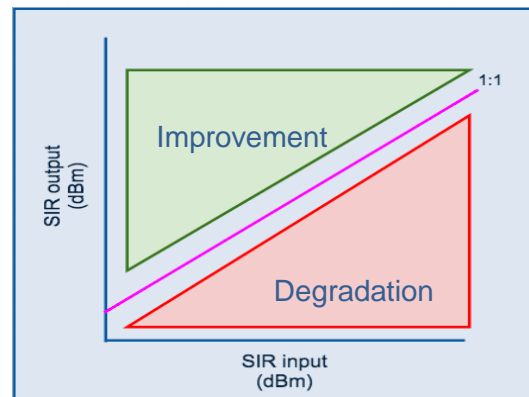


Figure 17: Results display format

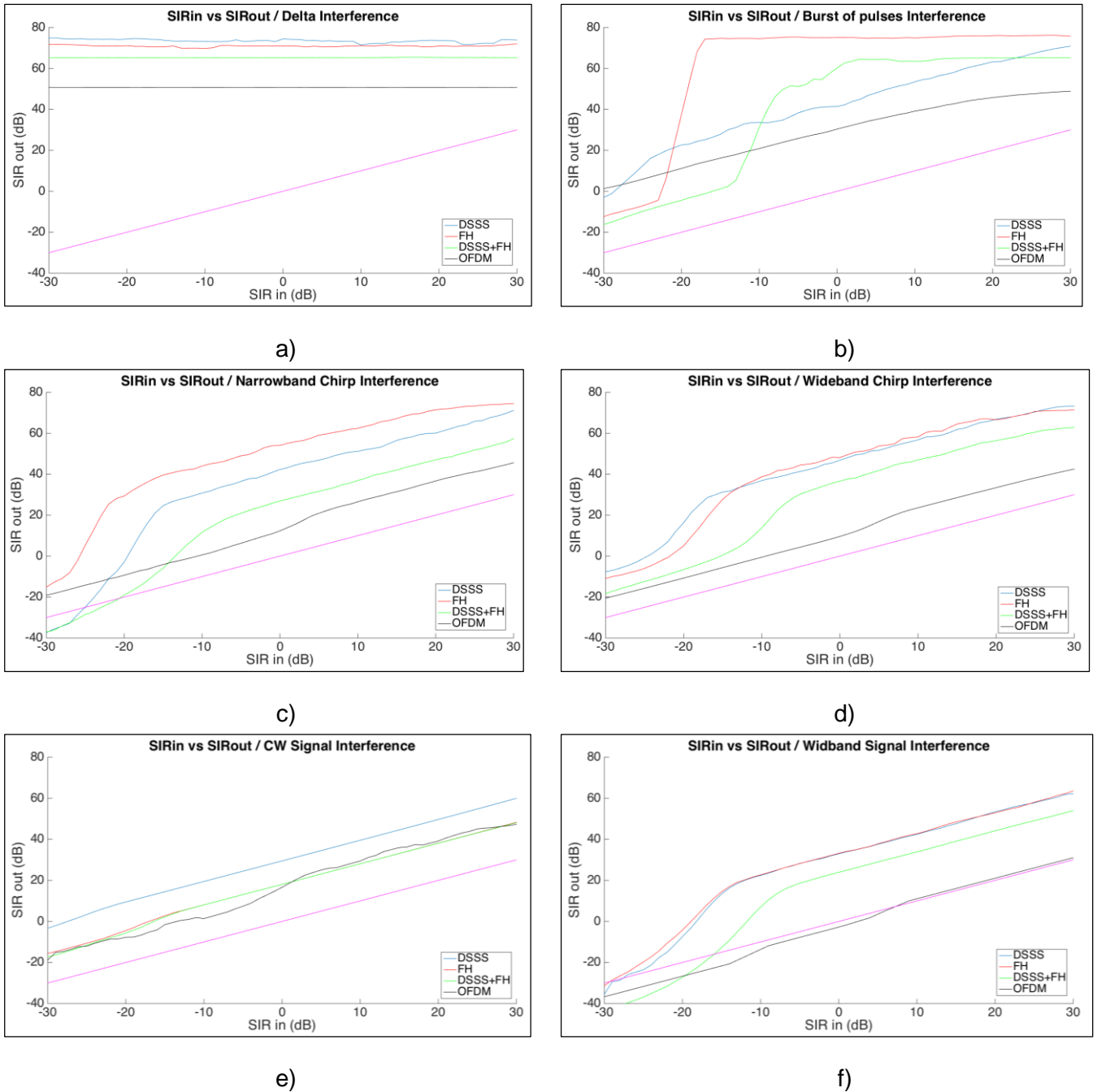


Figure 18: Results of the SIR study for every type of RFI signal: a) Delta/Glitch signal; b) Burst of pulses; c) Wideband Chirp; d) Narrowband Chirp; e) Continuous Wave and f) Wideband signal

According to results presented in Figure 18, it has become clear that the two modulations it could be said that works the best, the ones that provides greater robustness against the RFI signals under evaluation are the Frequency Hopping Spread Spectrum (FHSS) and Direct-Sequence Spread-Spectrum modulations.

Since FHSS is one of the two modulations that have obtained the best results in our simulations and it is already implemented in our transmitter, it will be the one configured to test its performance in a real scenario. But before the hardware implementation can be configured, a parametric study must be done in order to know how to achieve the best performance with the chosen modulation.

## 4.2. Parametric Study

Once the modulation that will be implemented with hardware has been chosen, a parametric study, in order to achieve the best performance, must be done. To do so, the performance of the modulation will be studied when the following parameters are changed:

- Number of subcarriers
- Sample per bit
- Bandwidth

The parametric study follows the same pattern as the SIR study before. The results will be reflected in a graph in which the vertical axis represents the SIR at the output and the horizontal axis represent the SIR at the input, both in decibels. Only the results for the burst of pulses, the narrowband chirp and the continuous wave Radio Frequency Interference (RFI) signals will be shown. Thereby, these results could be compared in a clearer way with the ones that will be obtained in section 5.3, in the hardware tests.

Figure 19 shows the first case where the number of subcarriers is changed and both samples per bit and bandwidth are constants. The case of 2, 4, 8 and 16 subcarriers will be simulated.

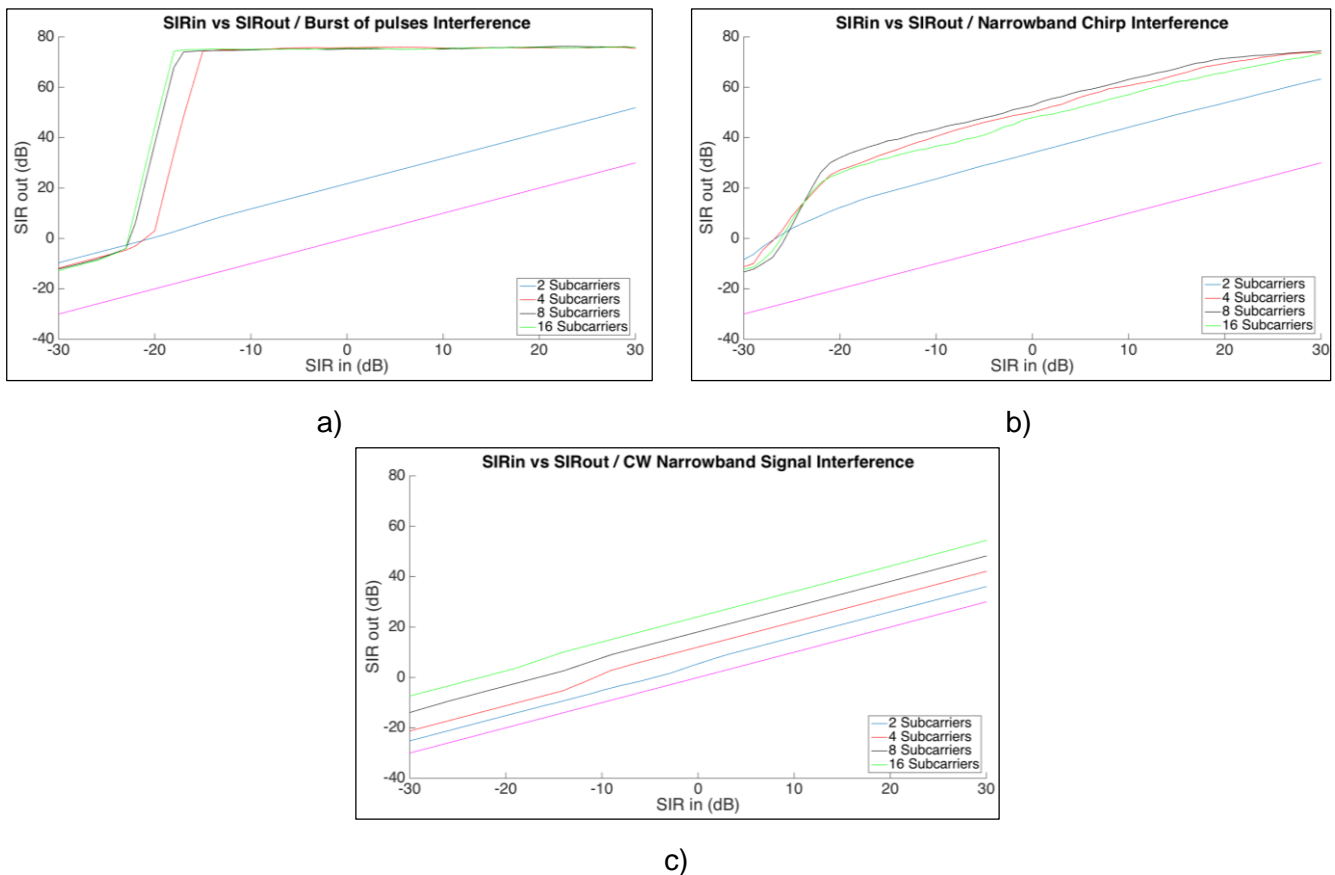


Figure 19: Performance of the FH for a changing number of subcarriers (2: blue; 4: red; 8: yellow; 16: green) in presence of: a) Burst of pulses Interference; b) Narrowband Chirp and c) Continuous Wave

According to the results obtained, the Frequency Hopping Spread Spectrum (FHSS) modulation works best as the number of subcarriers is increased. The clearer example is the case of the continuous wave RFI signal. This situation occurs because of the fact that when the number of subcarriers increases, the data to transmit is distributed over a bigger number of “sub-bands” and given that, the narrowband interference signal only spoils one subcarrier, the performance, when a major number of subcarriers integrate the modulation, is better.

The other two parametric studies are also relevant but not in the way the number of subcarriers can be. Those parameters (samples per bit and bandwidth) are fixed by the transmitter and receiver specifications and we will be limited in the hardware testing. On one hand, the samples per bit used in the definition of the original signal will be set according to the sampling frequency on the transmitter. On the other hand, the bandwidth that the modulation will use will be set according to the configuration of the transmitter.

In Figure 20 it is shown the study when the samples per bit is changed.

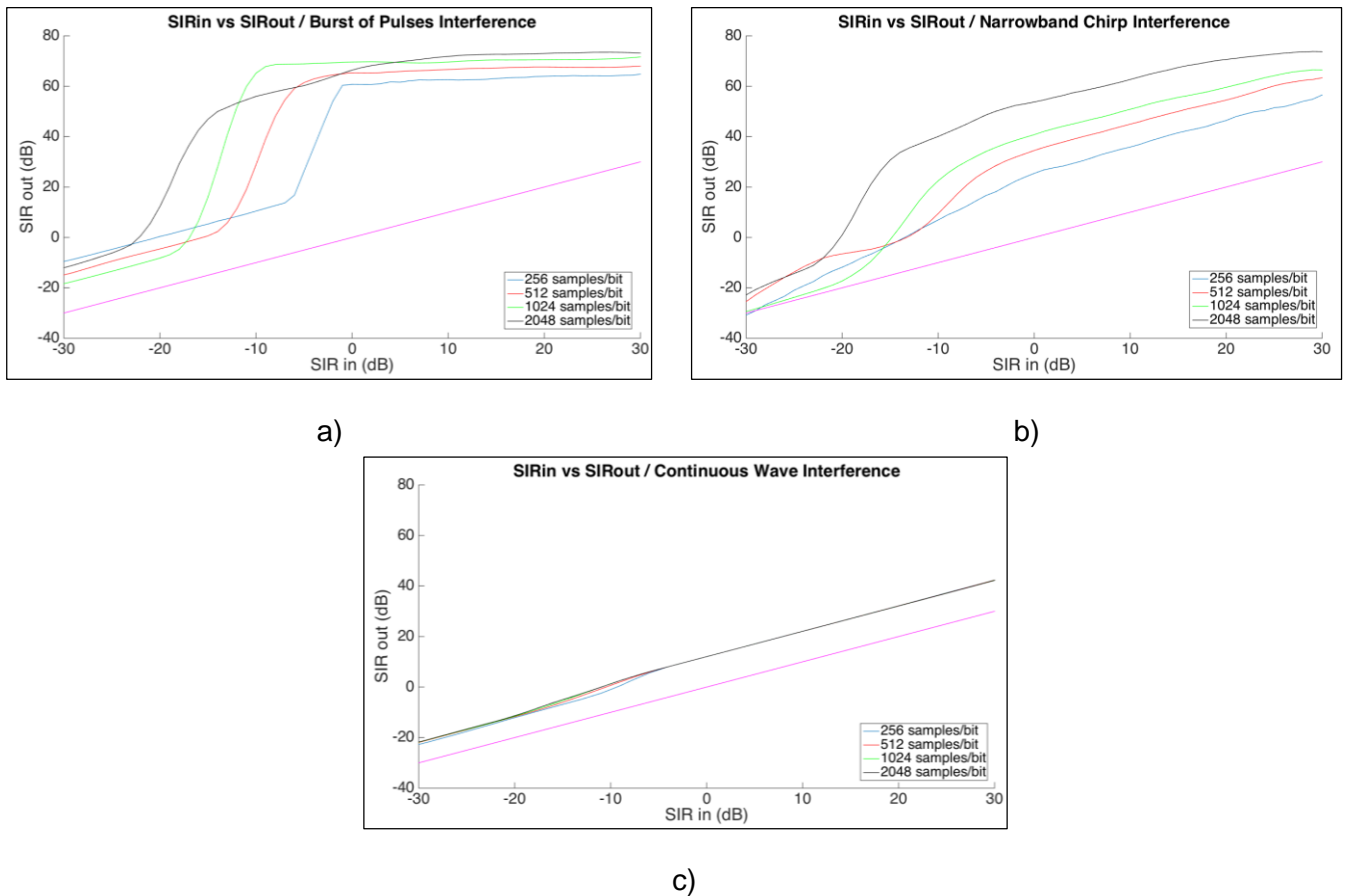


Figure 20: Performance of the FH for a changing number of samples per bit in presence of: a) Burst of pulses Interference; b) Narrowband Chirp and c) Continuous Wave

The figures plotted in Figure 20 suggest that the FHSS modulation works better as the number of samples per bit increase. This result is important but, as it was stated before, in the hardware implementation it will be a limitation because of the transmitter capabilities. The complete results will be shown on Appendix 3.



## **5. System physical Implementation**

The main goal of this section of the project is to implement the Frequency Hopping modulation using the available hardware in the laboratory and test its performance with real signals in a real scenario.

### **5.1. Hardware description**

First of all, an explanation of the hardware that will be used must be done. The main specifications for the 3DR transmitter and the RTL-SDR receiver will be exposed in Appendix 4.

#### **5.1.1. 3DR Transmitter**

The 3DR Radio transmitter is a small USB dongle that uses an open source firmware that gives us a lot of freedom of configuration and performance. This transmitter is easily configured using an open source program named “3DR Config” and it is managed from the MATLAB interface where the user can configure the exact signal to transmit.

#### **5.1.2. RTL-SDR Receiver**

RTL-SDR is a very cheap software defined radio that uses a DVB-T TV tuner dongle based on the RTL2832U chipset.

Radio components such as modulators, demodulators and amplifiers are traditionally implemented in hardware components. The advent of modern computing allows most of these traditionally hardware based components to be implemented into software instead. Hence, the software defined radio. This enables easy signal processing and thus cheap wide band scanner radios to be produced.

## **5.2. Hardware Implementation**

### **5.2.1. Transmitter Side**

First of all, the transmitter must be configured, setting the parameters according to our needs using the 3DR Config program. The 3DR will be configured to perform a Frequency Hopping Spread-spectrum (FHSS) modulation using three, five and seven subcarriers to see the performance for every case. Although many parameters of the transmitter can be adjusted, there are others that are internally configured and we must adapt to them. The 3DR is designed to work with another 3DR and for this reason when it does not find any partner with whom to associate the 3DR send continuously a sequence that our receiver will capture. The transmitter also implements a Gaussian Frequency-Shift Keying (GFSK) in order to modulate the data.

As it was mentioned before, the 3DR can be handled using MATLAB software. The first step, to set this device to transmit, is to define the serial port that will be used. After that, the port will be configured as needed and will be opened in order to allow the transmitter to send all the data. Once the configuration has been done, the code will enter in a “for” loop setting the 3DR to transmit every second a, known, data that has been previously established. Whenever the user wants to stop sending data the process will stop and the serial will be closed. The MATLAB code and the interface of 3DR Config program will be shown in Appendix 4.

### 5.2.2. Receiver Side

In this step the signal received has to be demodulated and compared to the one that was sent. In order to do it, first of all, the receiver is configured to start receiving data at a central frequency equal to 433 MHz with a sample rate of 256 kHz and a gain 1,49 dB. Once the receiver has read the data (two million samples) it is time to use MATLAB to demodulate the signal.

The demodulation steps followed at the receiver are shown in Figure 21.

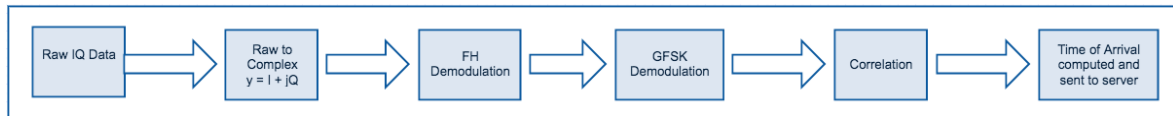


Figure 21: Diagram of the steps to demodulate the received signal

The raw, captured IQ data is 8 bit unsigned data. Each I and Q value varies from 0 to 255 (since, 000000002 = 0 and 111111112 = 255). To get from the unsigned (0 to 255) range it is needed to subtract 127.5 from each I and Q value, which results in a new range from -127.5 to +127.5. Then the complex data is simply  $y = I + jQ$ . After this step, the Frequency Hopping (FH) demodulation must take place. Afterwards, the Gaussian Frequency-Shift Keying must be demodulated as well, in order to extract the information. Once the sequence of ones and zeros the transmitter has sent is known, it is time to perform the correlation operation of the received signal with a known sequence that must appear if something has been transmitted. Using this correlation, the relative delay of the received signal can be estimated and therefore, send this value to the server that will compute the transmitter position.

The explanation of all the process with more details will be done in Appendix 4.

### 5.3. Signal-to-Interference Ratio Study

In this last step of our project, the results obtained in section 4.2 will be compared with the ones obtained in a real scenario. The idea of this study is to test the performance of the 3DR and the RTL-SDR in terms of Signal-to-Interference Ratio (SIR) at the output of the demodulator. The scope of the study will be the same as in section 4.2 but this time real signals will be used. Three types of different Radio Frequency Interference (RFI) signals will be generated (Burst of pulses, Continuous Waveform and Chirp signal) with the Signal Generator and observe the SIR at the output of the demodulator with a given Interference power at its entry.

Before the testing starts, the system must be calibrated. That means the SIR at the input of the receiver must be calculated using a known transmitter power and a known RFI signal power. Once the system has been calibrated and the exactly SIR at the input of the demodulator is known, the receiver can start capturing the data and computing the SIR when the signal has been through all the demodulation process.

The parameters for the configuration of the RFI signals and the images of the physical configuration of the system are shown in Appendix 4.



The results obtained are shown in Figure 22.

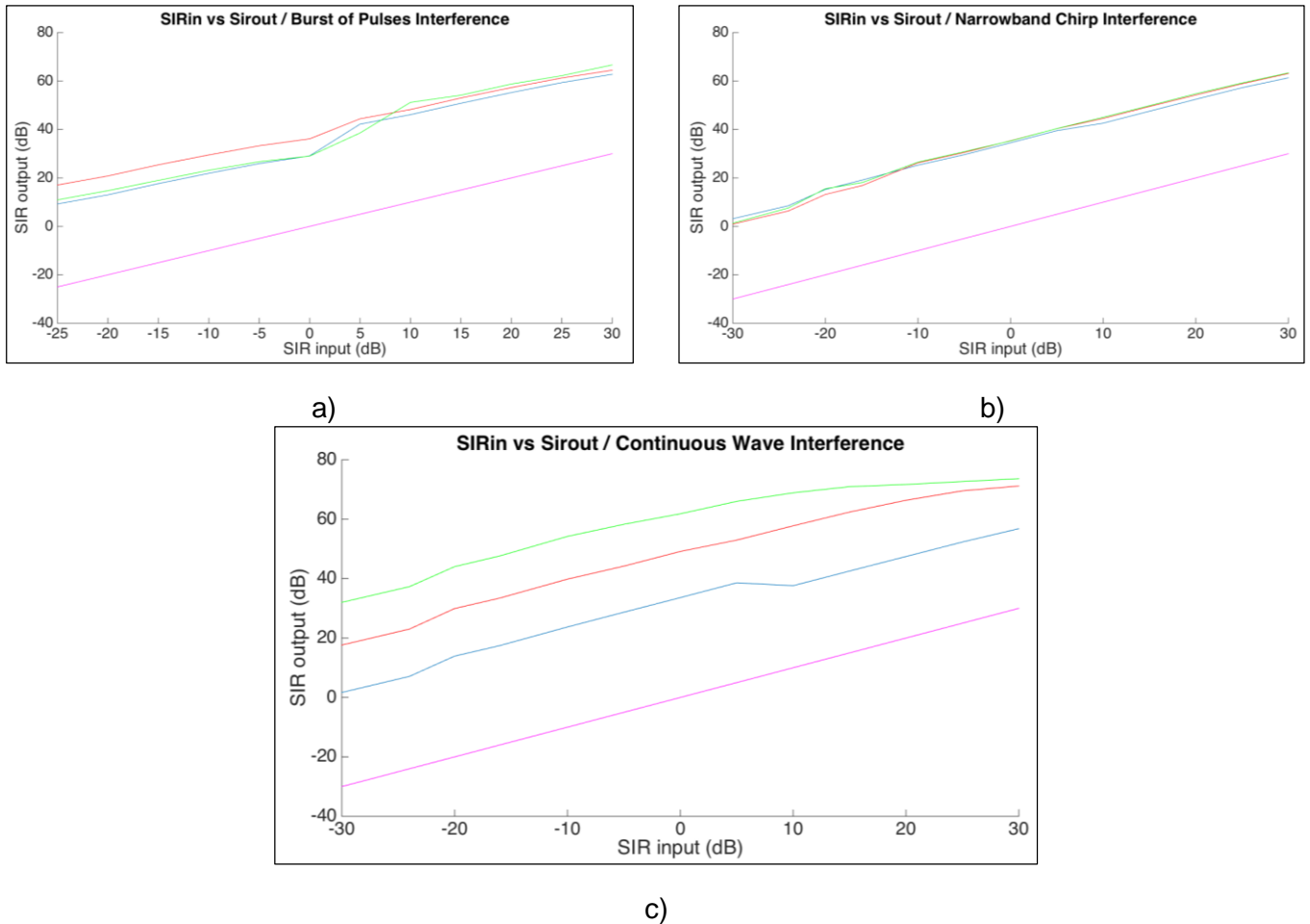


Figure 22: Performance of the FH for a changing number of subcarriers (3: blue; 5: red; 7: green) in presence of: a) Burst of pulses Interference; b) Narrowband Chirp and c) Continuous Wave

It can be observed that the results are closer to the ones obtained in section 4.2 where a parametric study was done. However, these results are not exactly the same as the previous ones and there are several reasons that explain why they are different from the simulated ones. First of all, there are some parameters, some configurations, that cannot be modified in the 3DR transmitter. One of them is the fact that the transmitter uses the whitening transformation. Another one is that it performs a Gaussian Frequency-Shift Keying (GFSK) modulation, as it was mentioned before, and therefore, a GFSK demodulation must be done in the receiver. This fact may have introduced some changes in the Signal-to-Interference Ratio (SIR) study.

It must be said that the Frequency Hopping Spread Spectrum (FHSS) implemented in the 3DR is not exactly the same that was simulated. That is because in the transmitter, in every hop it sends a beacon of data while in our simulation, a beacon of data was sent through all the subcarriers.

Despite what has been said above, the results are good, tests are satisfactory and the transmitter and receiver are working properly implementing the FHSS modulation.

## 6. Budget

The total budget of the project development is:

	Cost
Instruments	157.93 €
Materials	85 €
Personnel	6960 €
<b>Project</b>	<b>7202.93 €</b>

Table 1: Project Budget

The cost breakdown of materials, instruments and personal is:

Instrument	Price (€)	Years	Amortization/hour (€)	Used (h)	Cost (€)
Laptop	2000 €	6	0.0380517	720	27,39
MATLAB	2000 €	2	0.1141552	720	82,19
Vector Network Analyser ZVB 8	60.000 €	10	0.6849315	60	41.09
Signal Generator	10.000 €	10	0.1141552	60	6.85
Laboratory Instruments	600 €	10	0.0068493	60	0.41
<b>Total</b>					<b>157.93 €</b>

Table 2: Instrument budget

Material	Price (€)
GPS Antenna	30 €
3DR Radio v2	30 €
RTL-SDR Rafael Micro R820T	25 €
<b>Total</b>	<b>85 €</b>

Table 3: Material Budget

Name	Rank	€ hour/pers.	Total hours	Cost
Adriano Camps	Project Codirector	30	10	300 €
Jorge Querol	Project Codirector	30	30	900 €
Adrià Gil Sorribes	Junior Engineer	8	720	5760 €
			<b>Total</b>	<b>6960 €</b>

Table 4: Personnel Budget

## 7. **Conclusions and future development:**

Summarizing, the Robust Tracking System (RTS) simulator is working as expected and can provide a first estimation of the performance of the system. The simulations of different spread-spectrum modulations have been used to determine the best one in terms of robustness against RFI signals regarding the relationship between the SIR after and before for each modulation under evaluation. Frequency Hopping Spread-Spectrum has been the one that has achieved the best results and, therefore, it has been implemented with the available hardware at the laboratory. The transmitter and receiver are working properly and they are modulating and demodulating the data using the FHSS. The results from the test with real signals have reaffirmed the conclusions extracted from the parametric study and they have confirmed that the FHSS modulation provides our system a greater robustness of the order of 30 dB.

Future work has to be focused on integrating the three parts of the system and test it in order to see its performance in a real scenario. Furthermore, it would be interesting to create an application to gather all the information of the system and present it to the final customer in a more visual and interactive way.

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## Appendix 1:

### Spread Spectrum Modulations

#### A.1.1 Direct-Sequence Spread-Spectrum

A direct-sequence signal is a spread-spectrum signal generated by the direct mixing of the data with a spreading waveform (Pseudo-Random Noise) as shown in Figure 23:

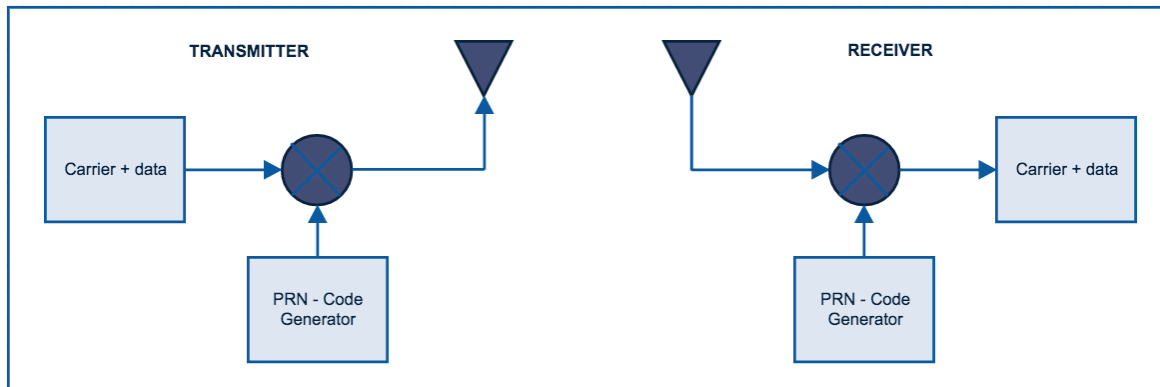


Figure 23: Block diagram of a basic DSSS system

Ideally, one would prefer a random binary sequence as the spreading sequence. However, practical synchronization requirements in the receiver force one to use periodic binary sequences. A shift-register sequence is a periodic binary sequence generated by combining the outputs of feedback shift registers. In our case we are using two Linear Feedback Shift Registers (LFSR) combined with a XOR operation, to generate the Pseudo-Random Noise Sequence, as shown in Figure 24:

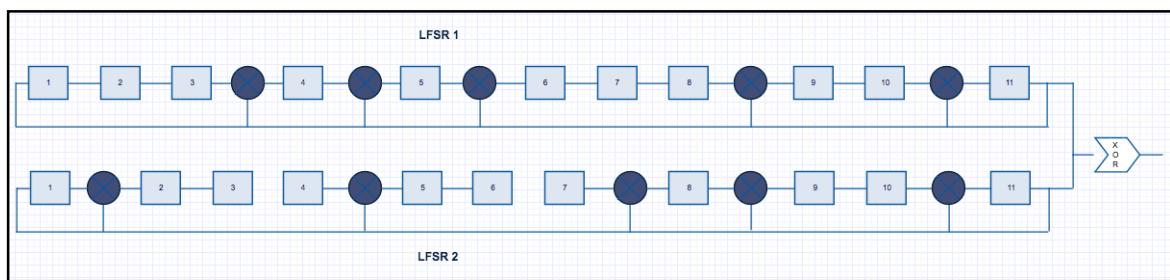


Figure 24: Linear Feedback Shift Registers configuration

The LFSR are defined by the following connections polynomials:

- $C(D)_1 = D^{10} + D^8 + D^5 + D^4 + D^3 + 1$
- $C(D)_2 = D^{10} + D^8 + D^7 + D^4 + D^1 + 1$

According to the LFSR theory the output sequence will be periodic with a period equal to  $L = 2^n - 1$  ( $n$  = polynomial degree) in the case of a primitive polynomial. In our case the sequence will have a period equal to 1023.

Table 5 show the ten first outputs of the Pseudo-Random Noise sequence generated in our simulations.

Clock Cycle	LFSR 1 state	LFSR 2 state	LFSR 1 output	LFSR 2 output	XOR output
1	1010000000	1010000010	0	0	0
2	0101000000	0101000001	0	1	1
3	0010100000	1111101101	0	1	1
4	0001010000	1010111011	0	1	1
5	0000101000	1000010000	0	0	0
6	0000010100	0100001000	0	0	0
7	0000001010	0010000100	0	0	0
8	0000000101	0001000010	1	0	1
9	1011100111	0000100001	1	1	0
10	1110010110	1101011101	0	1	1

Table 5: First 10 outputs of the PRN Sequence in the DSSS modulation

### A.1.2 Frequency Hopping Spread-Spectrum

Frequency hopping is the periodic changing of the carrier frequency of a transmitted signal. The basic system is described in Figure 25.

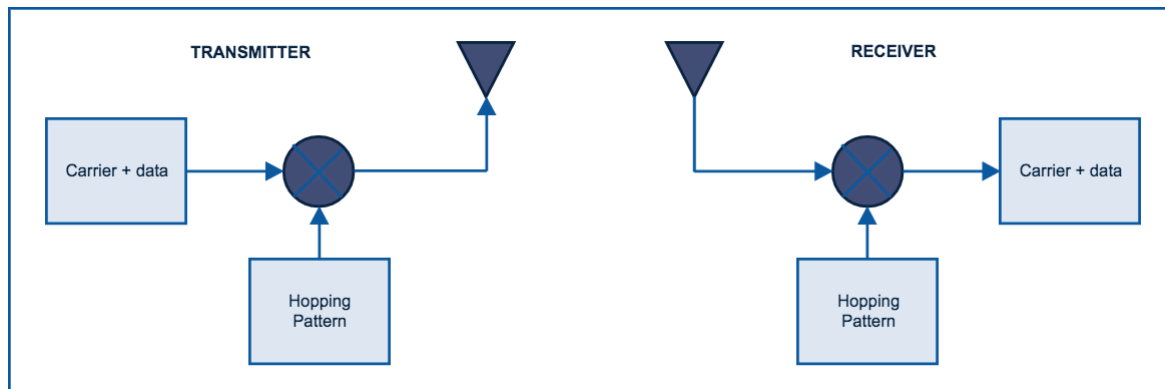


Figure 25: Block diagram of a basic FHSS system

The sequence of carrier frequencies is called the frequency-hopping pattern. The set of  $M$  possible carrier frequencies  $\{f_1, f_2, \dots, f_M\}$  is called the hopset. The rate at which the carrier frequency changes is called the hop rate. Hopping occurs over a frequency band called the hopping band that includes  $M$  frequency channels. Each frequency channel is defined as a spectral region that includes a single carrier frequency of the hopset as its centre frequency and has a bandwidth  $B$ . The hopping band has bandwidth  $W \geq MB$ .



### A.1.3 Orthogonal Frequency-Division Multiplexing

OFDM is based on the well-known technique of Frequency Division Multiplexing (FDM). In FDM different streams of information are mapped onto separate parallel frequency channels. Each FDM channel is separated from the others by a frequency guard band to reduce interference between adjacent channels. OFDM basic system configuration is shown in Figure 26.

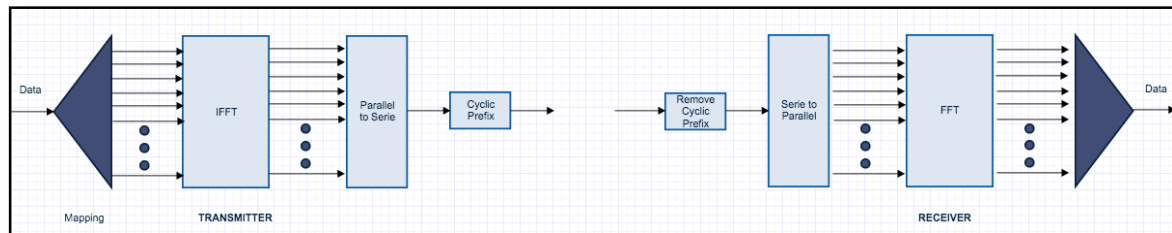


Figure 26: Figure 23: Block diagram of a basic OFDM system

The OFDM scheme differs from traditional FDM in the following interrelated ways:

1. Multiple carriers (called subcarriers) carry the information stream,
2. The subcarriers are orthogonal to each other, and
3. A guard interval is added to each symbol to minimize the channel delay spread and Inter symbol interference (ISI).

Figure 25 illustrates the main concepts of an OFDM signal and the inter-relationship between the frequency and time domains. In the frequency domain, multiple adjacent tones or subcarriers are independently modulated each one with complex data. An Inverse FFT transform is performed on the frequency-domain subcarriers to produce the OFDM symbol in the time-domain. Then in the time domain, guard intervals are inserted between each of the symbols to prevent inter-symbol interference at the receiver caused by multi-path delay spread in the radio channel. Multiple symbols can be concatenated to create the final OFDM burst signal. At the receiver an FFT is performed on the OFDM symbols to recover the original data bits.

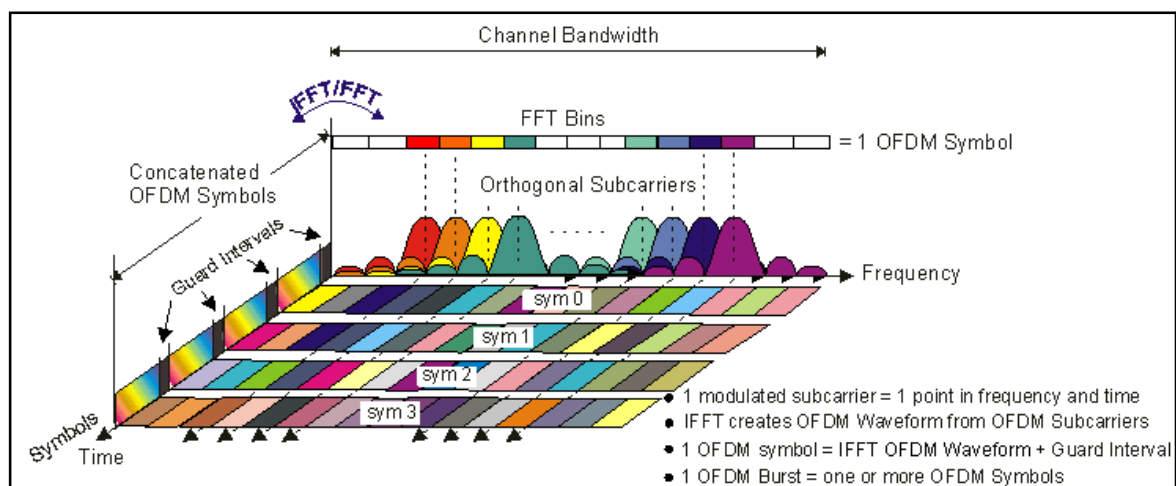


Figure 27: OFDM main concepts

#### A.1.4 5G Modulations

As it was mentioned in section 2, in this project, four 5G modulations will be studied:

- filtered-Orthogonal Frequency-Division Multiplexing (f-OFDM)
- Generalized Frequency-Division Multiplexing (GFDM)
- Filter Bank Multi-Carrier (FBMC)
- Universal Filtered Multi-Carrier (UFMC)

The main goal of these modulations is to overcome the main weakest points of the OFDM and in the following lines it will explained which advantages introduce every one of them.

##### **Filtered Orthogonal frequency-division multiplexing (f-OFDM)**

To avoid the above-mentioned limitations of OFDM and to meet the new challenges faced by 5G waveform, a new enabler for flexible waveform is proposed, named as filtered-OFDM (f-OFDM). With subband-based splitting and filtering, independent OFDM systems (and possibly other waveforms) are closely contained in the assigned bandwidth. In this way, f-OFDM is capable of overcoming the drawbacks of OFDM whilst retaining the advantages of it. First of all, with subband-based filtering, the requirement on global synchronization is relaxed and inter-subband asynchronous transmission can be supported. Secondly, with suitably designed filters to suppress the out of bounds emissions (OOBE), the guard band consumption can be reduced to a minimum level. Thirdly, within each subband, optimized numerology can be applied to suit the needs of certain type of services.

##### **Generalized Frequency-division multiplexing**

With Generalized Frequency-Division Multiplexing (GFDM) a generalization of OFDM is proposed. This generalization introduces additional degrees of freedom when choosing the system parameters. The new scheme offers more flexibility by ordering the data in a two-dimensional time-frequency block structure, introducing flexible pulse shaping for the individual subcarriers and potentially reducing the amount of CP when compared to the amount of useful data, while still providing means for an efficient single-tap equalization in frequency domain. A technique called tail biting is employed to eliminate the need for additional guard periods that would be necessary in a conventional system, in order to compensate for filtering tails and prevent overlapping of subsequent symbols. However, adding more flexibility to the system is traded for the orthogonality of subcarriers. Using a pulse shape with strong frequency localization introduces self-created inter-symbol interference (ISI) and inter-carrier interference (ICI). This can be mitigated by employing interference cancellation techniques.

### **Filter Bank Multicarrier**

Filter Bank Multicarrier (FBMC) are a subclass of multicarrier (MC) systems and have their roots in the pioneering works of Chang and Saltzberg who introduced multicarrier techniques over two decades before the introduction and application of OFDM to wireless communication systems. FBMC modulation can be considered as an evolved OFDM. The filter banks address the main disadvantages of OFDM: a loss in spectral efficiency due to CP insertion, higher out-of-band radiating (since the subcarriers have sinc-like frequency behaviour), and a higher sensitivity to narrowband interferers.

First, in FBMC their subchannels can be optimally designed in the frequency domain to have desired spectral containment. Second, this systems do not require redundant CP and thus are more spectral efficient.

With high enough out-of-band attenuation of the sub-band filters, the filter bank itself can provide sufficient frequency isolation to implement the needed reception and selectivity. This enables you to move all signal processing functions after the filter bank to the low sampling rate.

### **Universal-filtered Multicarrier**

This 5G waveform can be considered as an enhancement of CP-OFDM. It differs from FBMC in that instead of filtering each subcarrier individually, UPMC splits the signal into a number of sub-bands, which it then filters. UPMC does not have to use a cyclic prefix, although one can be used to improve the inter-symbol interference protection.

## Appendix 2:

### Robust Tracking System Simulation

As it was mentioned before, after the simulation has been done, the user is able to observe the signals that have been part of it. On one hand, the signals in the transmitter side are displayed in one panel as shown in Figure 28.

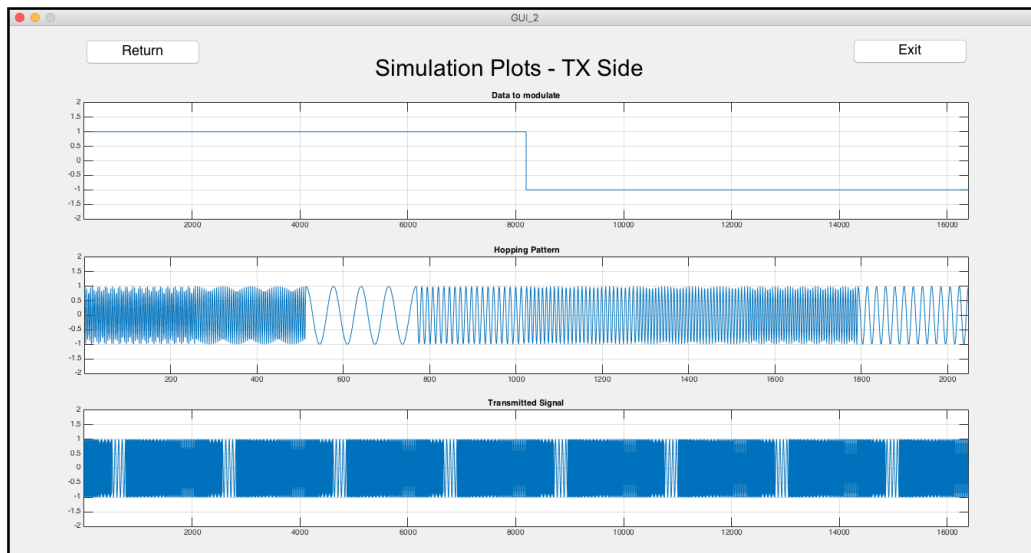


Figure 28: Signals on the transmitter side of the simulation

On the other hand, the signals processed in the receiver are displayed in another panel just like in Figure 29.

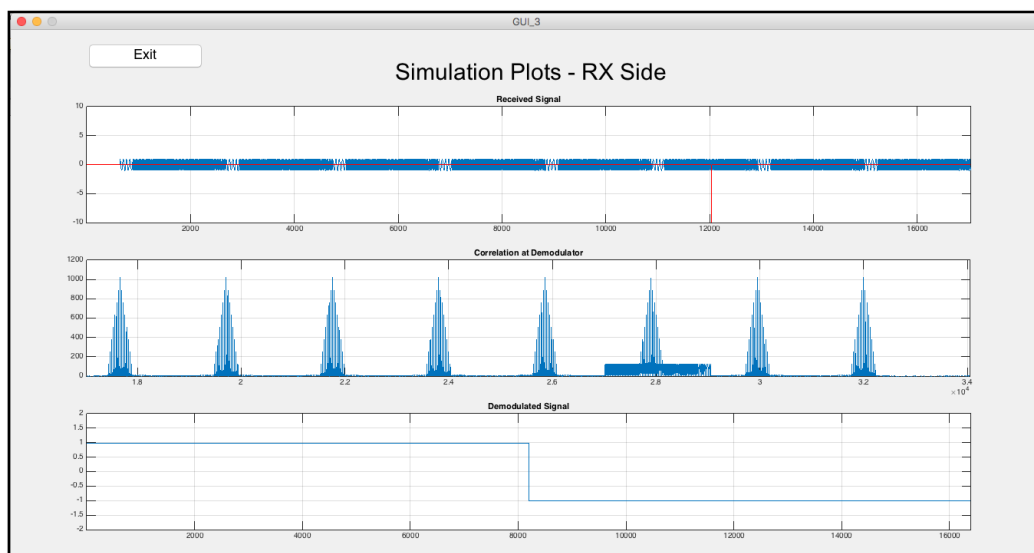


Figure 29: Signals on the receiver side of the simulation

Those plots are practically equal to the ones explained in section 3.2 where an explanation of the simulation of the spread-spectrum modulations is done.

A visual comparison between two simulations is done as it was stated earlier on in section 3.1. In the first simulation the received signal has a normal-high Signal-to-Interference Ratio (SIR). On the other hand, in the second simulation, the received signal has a low SIR.

- First simulation results

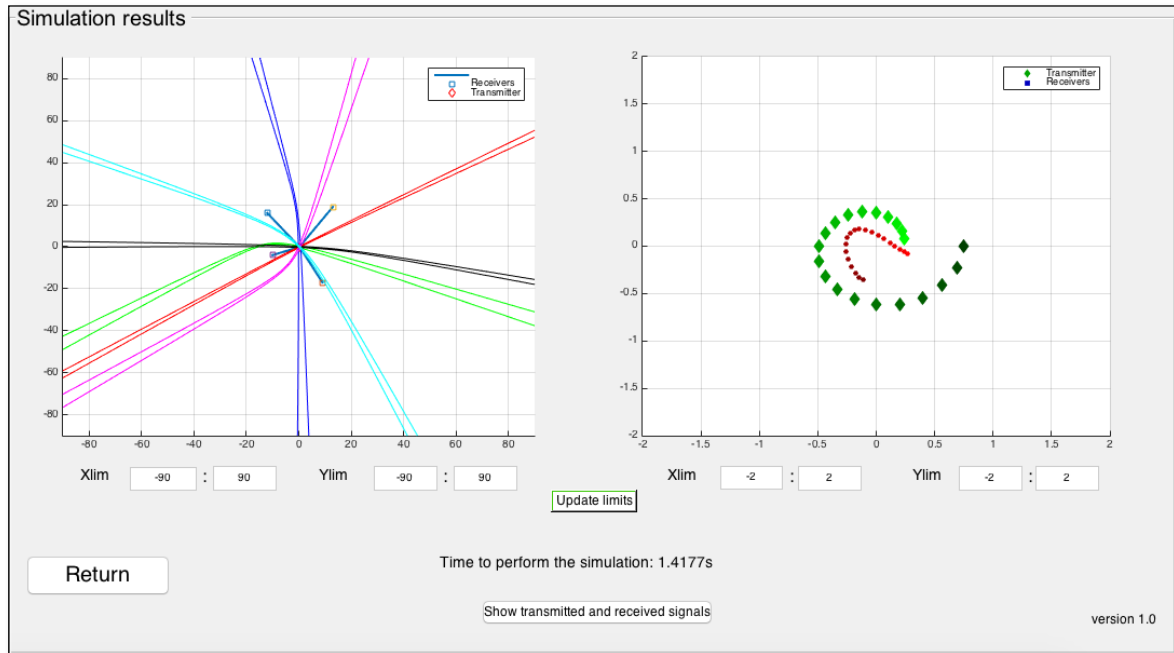


Figure 30: Simulation with normal-high SIR at the receiver

- Second simulation results

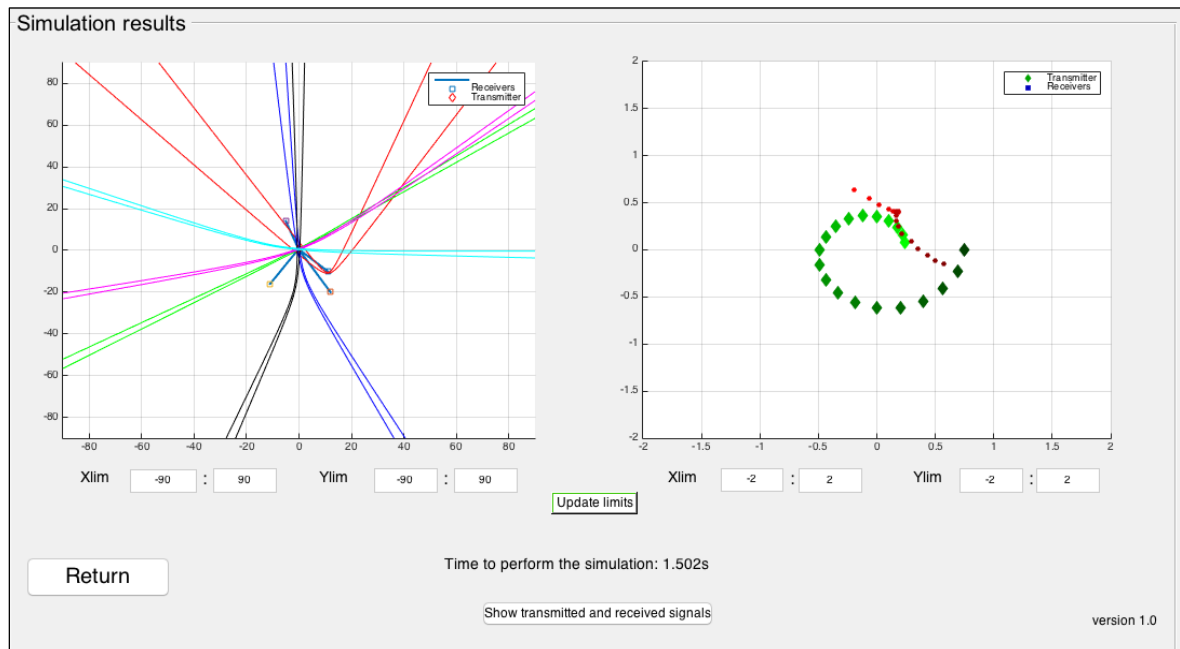


Figure 31: Simulation with low SIR at the receiver

## Appendix 3:

### Parametric Study

In the following section the complete results of the parametric study are shown.

- Number of Subcarriers

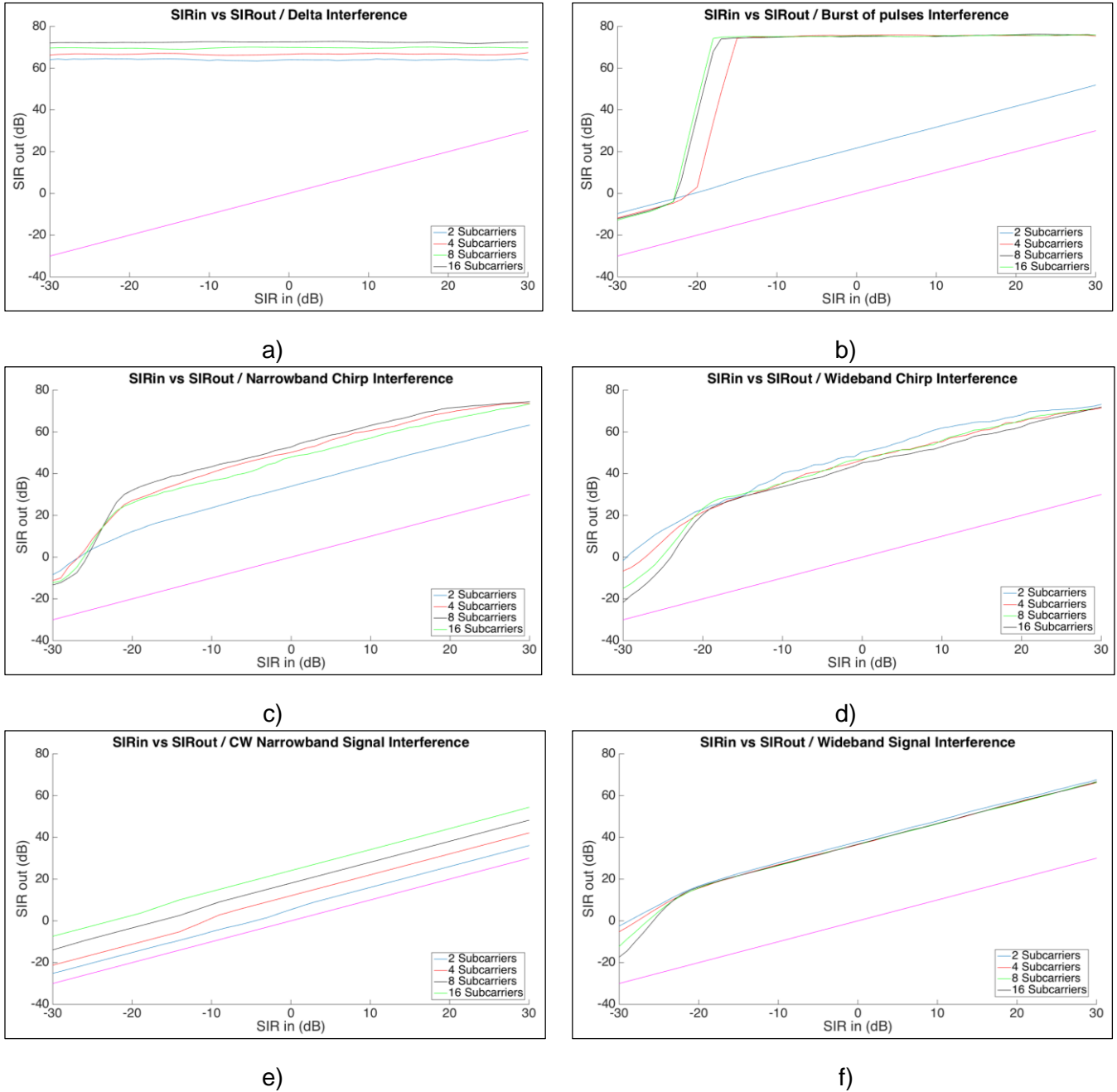
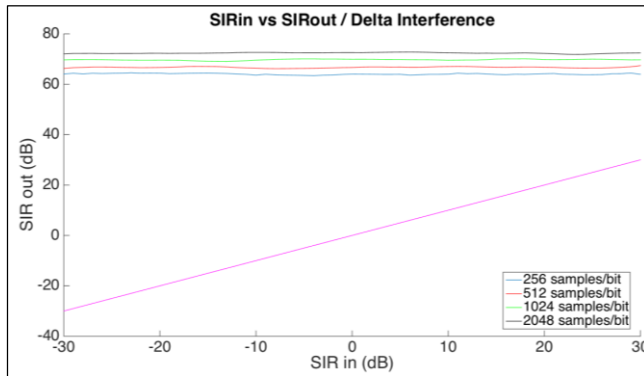
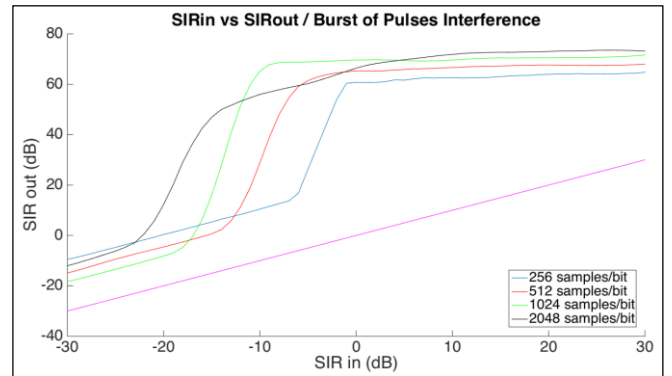


Figure 32: Performance of the FH for a changing number of subcarriers in presence of: a) Delta Interference; b) Burst of Pulses; c) Wideband Chirp; d) Narrowband Chirp; e) Continuous Wave and c) Wideband Signal; RFI

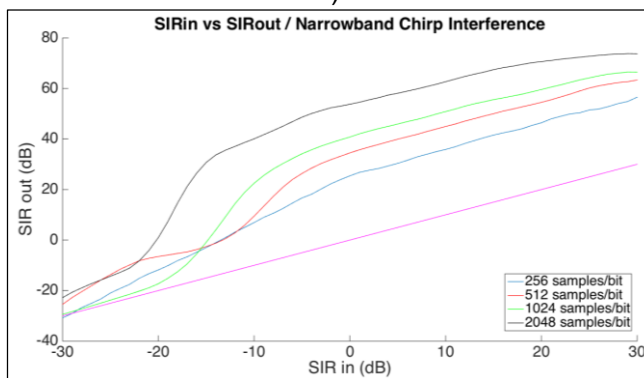
- Samples per bit



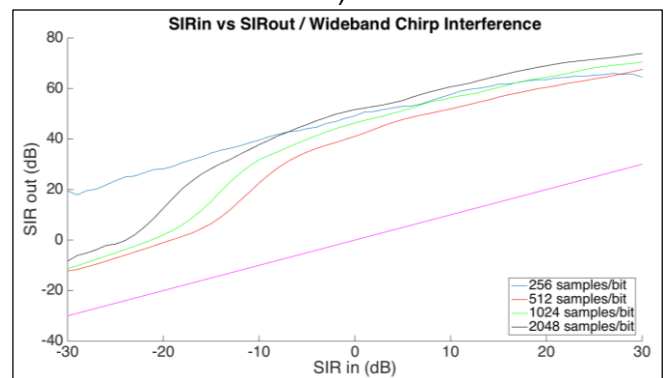
a)



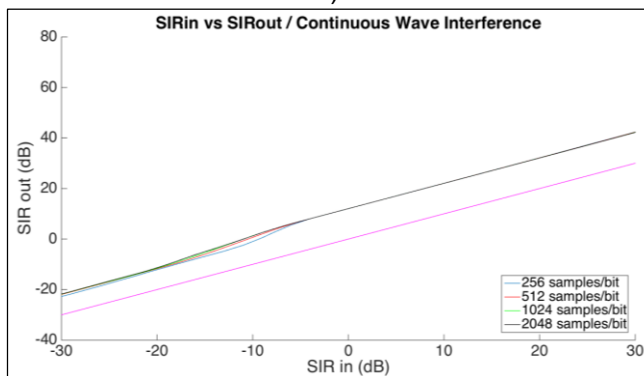
b)



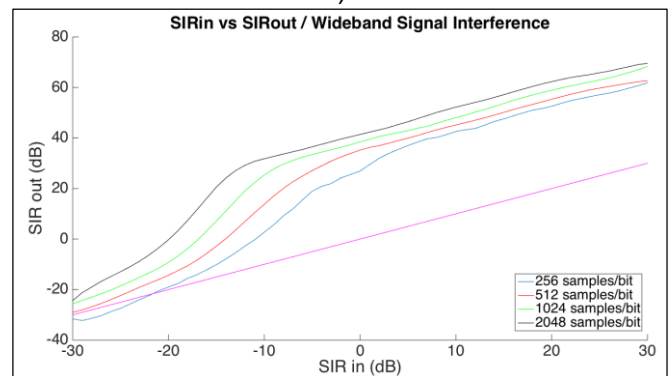
c)



d)



e)

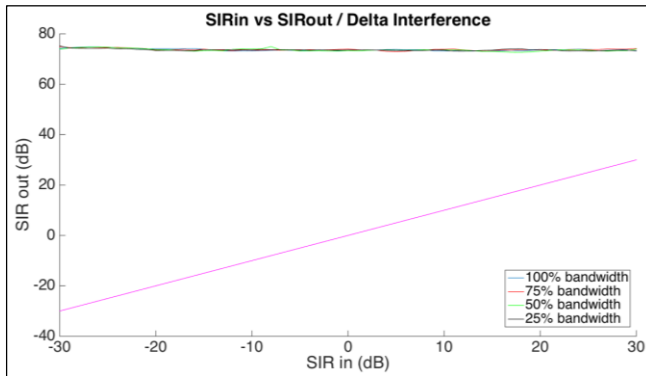


f)

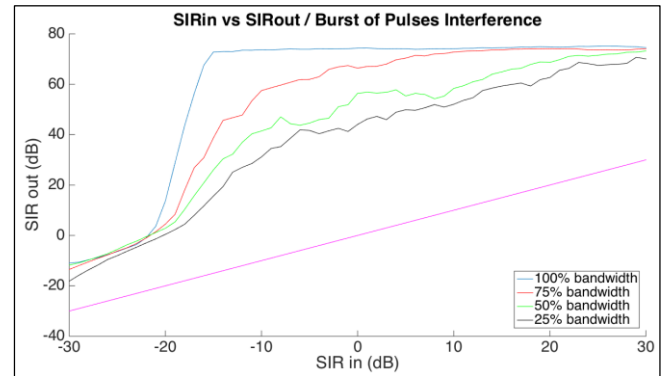
Figure 33: Performance of the FH for a changing number of samples per bit in presence of: a) Delta Interference; b) Burst of Pulses; c) Wideband Chirp; d) Narrowband Chirp; e) Continuous Wave and f) Wideband Signal; RFI

This two first studies show clearly that the Frequency Hopping Spread-Spectrum (FHSS) modulation works better as the number of subcarriers increases and the number of samples per bit increases. In the first case, changing the number of subcarriers have more incident when the signal is disturbed by a narrowband interference. On the other hand, increasing the samples per bit provides greater robustness against wideband RFI.

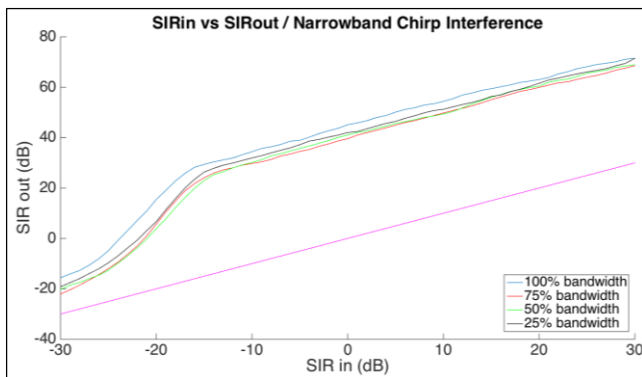
- Bandwidth



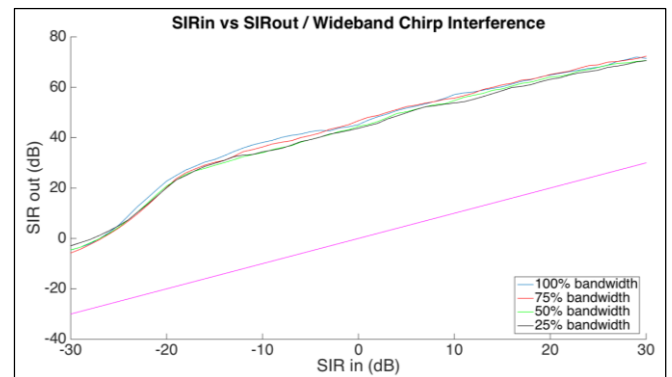
a)



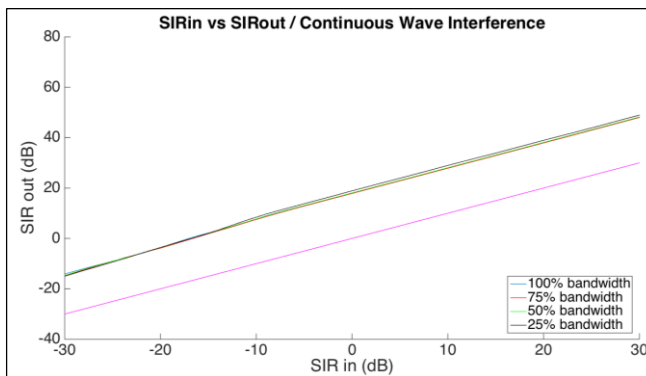
b)



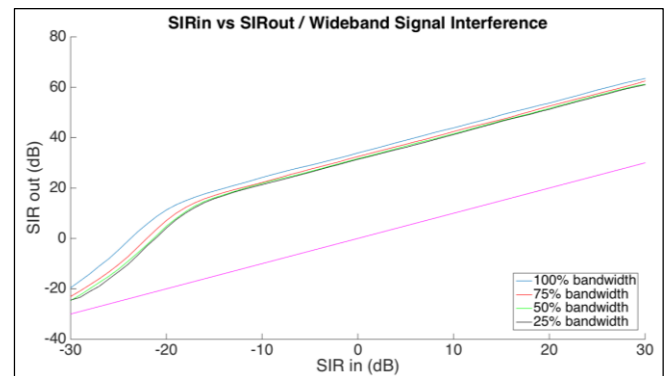
c)



d)



e)



f)

Figure 34: Performance of the FH for a changing available bandwidth in presence of: a) Delta; b) Burst of Pulses; c) Wideband Chirp; d) Narrowband Chirp; e) Continuous Wave and f) Wideband Signal RFI

The bandwidth study is not as relevant as it was originally though. The conclusion is to set the bandwidth according to the specifications of the system and the needs of the user.



## Appendix 4:

### Hardware Description and configuration

#### A.4.1 Transmitter 3DR:

The basic specifications of the transmitter are the following:

- Band: 433MHz
- Antenna Connector: RP-SMA connector
- Output power: 100mW (20dBm), adjustable between 1-20dBm
- Interface: Standard TTL UART
- LED connection indicators
- Data rates up to 250kbps (Air rate)
- MAVLink framing protocol and status reporting
- Frequency hopping spread spectrum (FHSS)
- Adaptive division multiplexing time (TDM)
- Built in error correction code (you can correct up to 25% bit errors data)

Based on the radio module HopeRF HM-TRP, offering a microcontroller RF SI1000 SiLabs.



Figure 35: 3DR Transmitter

The program used to configure the transmitter is the 3DR Config and its interface is shown in Figure 30.

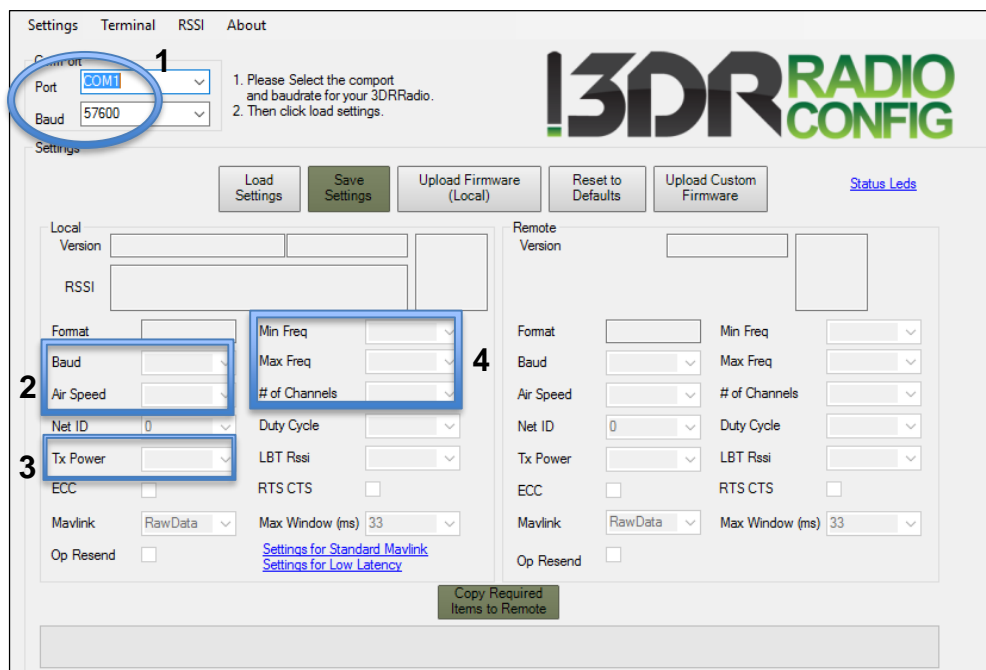


Figure 36: 3DR Config interface

The process to configure the transmitter with 3DR Config are explained below:

1. We must choose, in the first place, the COM port where the 3DR is connected and the baud rate configured in the transmitter.
2. The Baud Rate: from 1200 to 115200 bps and the Air Baud rate: from 2000 to 250000 bps are configured
3. Transmitter power is set. Available values are from 1dBm to 20dBm.
4. Finally, the bandwidth and the number of channels are set.

#### A.4.2 Receiver RTL-SDR:

The basic specifications of the transmitter are the following:

- Frequency range from 24 MHz to 1766 MHz.
- Maximum sample rate equal to 2,4MS/s.
- Native resolution of 8 bits, but the Effective Number of Bits (ENOB) is estimated at ~7 bits.
- Minimum receiver sensitivity: -100 dBm.



Figure 37: RTL-SDR Receiver

Using the terminal we can change the options and default settings for the rtl-sdr utility,

```
rtl_sdr, an I/Q recorder for RTL2832 based DVB-T receivers
Usage: [-f frequency_to_tune_to [Hz]]
        [-s samplerate (default: 2048000 Hz)]
        [-d device_index (default: 0)]
        [-g gain (default: 0 for auto)]
        [-p ppm_error (default: 0)]
        [-b output_block_size (default: 16 * 16384)]
        [-n number of samples to read (default: 0, infinite)]
        [-S force sync output (default: async)]
        filename (a '-' dumps samples to stdout)
```

Figure 38: Syntax to set the receiver main configuration parameters

## Hardware Implementation

In the following section a detailed explanation of the configuration and the implementation of both transmitter and receiver, in order to work together, is done. In the first place, the transmitter must be configured using the program as described before setting the parameters as stated below.

- **Baud Rate** = 4800 and **Air Rate** = 8000
- **Power** equal to 20 dBm.
- **Min frequency** = 433000; **Max frequency** = 433300; **# of channels** = 3,5 or 7.

Once the transmitter has been configured we must proceed to the transmission of the signal. To do so, we execute the following script on MATLAB.

%%  
 %%% Author: Adrià Gil Sorribes %%%  
 %%% Robust Tracking System %%%  
 %%%

%Configure the Serial Port where the transmitter is connected

```
DR = serial('COM4', 'OutputBufferSize', 20000);
```

%Open the serial port to allow the transmitter to send the signal

```
fopen(DR)
```

```
T = 1;
```

%Define the signal to transmit

```
signal_tx = 'adriaadriaadriaadria';
```

```
save('t','T');
```

%Send the data every second while the user wants

```
while (exist('t.mat','file'))
```

```
    fprintf(DR, signal_tx);
```

```
    pause(1)
```

```
end
```

%Close the connection of the serial port

```
fclose(DR)
```

The transmitter will start to send the described data every second. While the 3DR is transmitting the data, we execute the command shown on Figure 39 to set the RTL-SDR to receive the data.

```
admin$ rtl_sdr -f 433102000 -g 2 -s 256000 -n 2000000 txttest.dat
```

Figure 39: Command to set the RTL-SDR to capture data

Once all the data has been captured it is time to demodulate it to extract the valuable information. First, the captured raw data is transformed to complex information as it was explained on section 5.2.2. After that, the GFSK demodulation must take place. This demodulation is performed using filters at the frequencies where the valuable data is placed and setting the samples allocated at the frequency superior to 1 and the samples allocated at the frequency below to 0. After this step the sequence of zeros and ones is correlated with the sequence that the transmitter has sent. Finally, it is detected where it was a transmission and the time of arrival is sent to the server.

All this process has been implemented with the 3DR and the RTL-SDR and two laboratory instruments, the Signal Generator and the Spectrum Analyser. Furthermore, AD converters and attenuators have been also used in the assembly.

Figure 40 show the physical connections of the system:

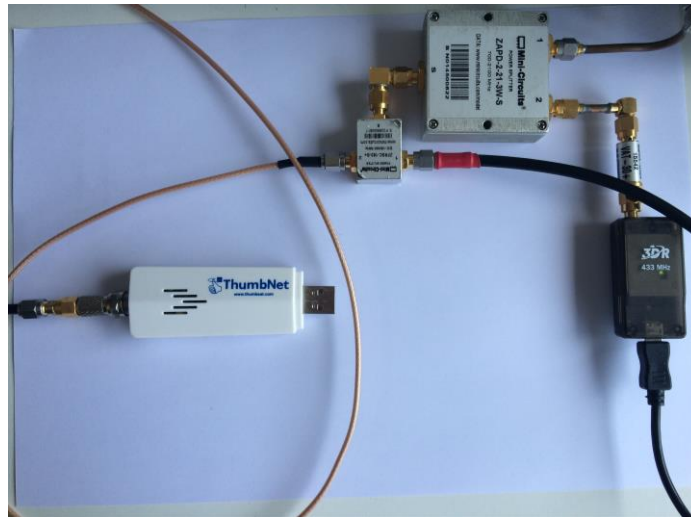


Figure 40: Physical connections between 3DR and RTL-SDR

Figure 41 show the two laboratory instruments used in the tests:

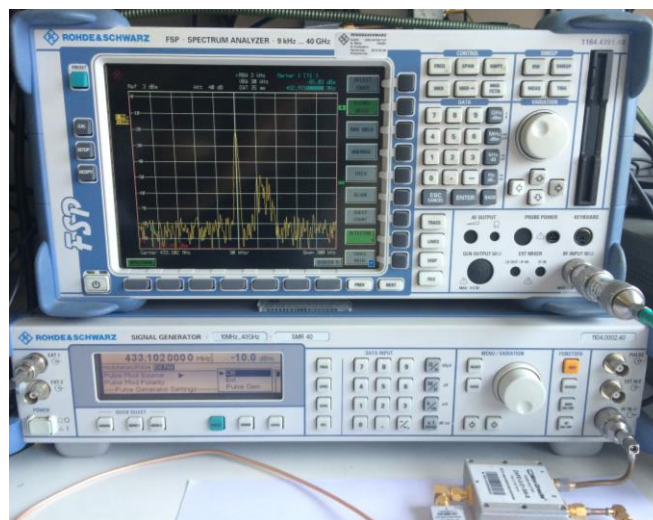


Figure 41: Laboratory Instruments used to obtain the results in the tests

In Figure 41, the top one instrument is the Spectrum Analyser which will show graphically every signal that is part of the test. The bottom one is the signal generator which will create the Radio Frequency Interference (RFI) signals. These RFI signals are created using the following configuration:

- Central frequency = 433.090 MHz (3 Subcarriers); 433.102 MHz (5 Subcarriers) and 433.121 MHz (7 Subcarriers)

The fact that the central frequency is changing according to how many subcarriers are configured in the transmitter is because depending on the number of subcarriers, the central frequency of the transmitted signal changes and therefore the central frequency of the RFI signal must change in order to extract the best results possible.

- Continuous Wave RFI signal

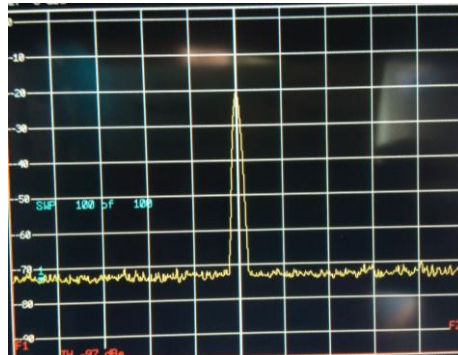


Figure 42: Continuous Wave RFI signal

- Burst of pulses RFI signal
  - Signal modulation: Pulse
  - Pulse Width: 100  $\mu$ s
  - Pulse Repetition: 2ms

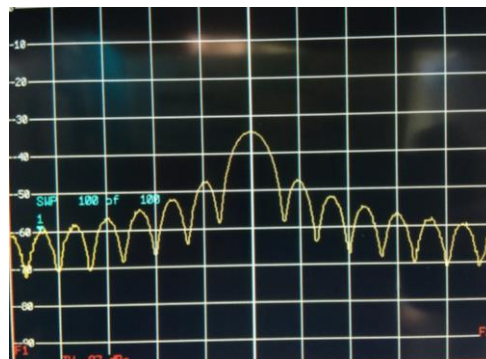


Figure 43: Burst of pulses RFI signal

- Narrowband Chirp RFI signal
  - Signal modulation: FM
  - FM deviation: 50 kHz

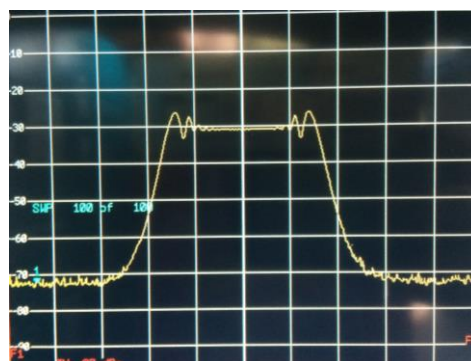


Figure 44: Narrowband Chirp RFI signal

Using the RFI signals described above the system has been tested and the results obtained have been exposed on section 5.3.

## **Glossary**

**CW** Continuous Waveform

**DPSK** Differential Phase-Shift Keying

**DSSS** Direct-Sequence Spread-Spectrum

**FFT** Fast Fourier Transform

**FHSS** Frequency Hopping Spread Spectrum

**FBMC** Filtered Bank Multi-Carrier

**f-OFDM** filtered Orthogonal Frequency-Division Multiplexing

**GFDM** Generalized Frequency-Division Multiplexing

**GFSK** Gaussian Frequency-Shift Keying

**GNSS** Global Navigation Satellite System

**GPS** Global Positioning System

**GUI** Graphic User Interface

**IFFT** Inverse Fast Fourier Transform

**LFSR** Linear Feedback Shift Register

**LMS** Least Mean Squares

**MEO** Medium Earth Orbit

**NMEA** National Marine Electronics Association

**OFDM** Orthogonal Frequency-Division Multiplexing

**OOBE** Out Of Bounds Emissions

**PRN** Pseudo-Random Noise

**RFI** Radio Frequency Interference

**RTS** Robust Tracking System

**SIR** Signal-to-Interference Ratio

**SNR** Signal-to-Noise Ratio

**TDOA** Time Difference of Arrival

**TOA** Time of Arrival

**UFMC** Universal Filtered Multi-Carrier